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GAMMA, ELECTRON, AND PROTON RADIATION EXPOSURES OF P-CHANNEL, ENHANCEMENT, METAL OXIDE SEMICONDUCTOR, FIELD EFFECT TRANSISTORS

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Greenbelt, Maryland

SUMMARY

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P-channel enhancement MOS insulated gate field effect transistors were irradiated with either Co60 gammas, 2 Mev electrons, or 22 Mev protons. These devices experienced significant increase in gate threshold voltage. The devices were biased during exposure. The rate of increase in gate threshold voltage appears to be a function of the amount of bias during exposure. Although transconductance was changed, no significant trend toward either increase or decreasing with radiation dose was apparent.

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INTRODUCTION

An exciting semiconductor device developed in recent years is an insulated gate field effect device called the metal-oxide-semiconductor field effect transistor, or MOSFET. Some of the praises of the MOSFET are sung by Donald C. Lokerson in a NASA report (1). The type of MOSFET used in the system (IMP D & E encoder) discussed by Mr. Lokerson is a P-channel enhancement transistor that is symetrical, i.e., the drain and source are interchangeable. Three of these devices as a monolithic structure are connected in series and packaged in a TO 5 can, to form a logic element which is shown schematically in Figure 1.

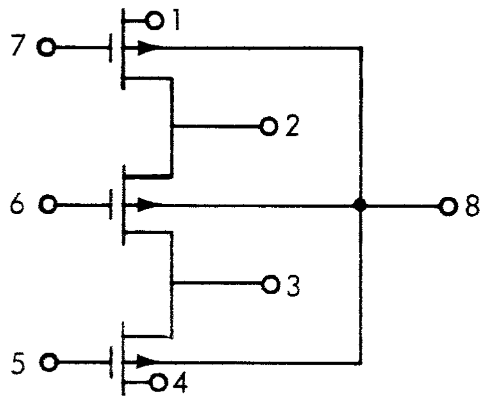

Figure 1. Schematic Diagram of Logic Element.

Pins 1, 2, 3 & 4 can be either source or drain. Pins 5, 6 & 7 are gates and pin 8 is the body.

This device, manufactured by General Micro-Electronics, is called SC1128. Its lower gate threshold counterpart is the SC1129. As mentioned before, it is one of the logic blocks for IMP D & E and its response to radiation is the subject of this report.

This report covers three types of radiation that one must be concerned with when considering space radiation effects; namely, gammas, electrons, and protons. Although trying to duplicate exactly the spectrum that one might encounter on a space mission is impossible, I believe that the energies of the radiation used, are high enough to be representative of the general radiation evnironment in space. The energies about which I speak are Co^{60} for gammas, 2 Mev for electrons and 22 Mev for protons. One further introductory comment, this study is engineering in nature. I make no attempt to evaluate the results in terms of what happens to the semiconductor, the oxide, or the surface. I do not think there is enough information here to justify that kind of evaluation.

THE EXPERIMENTS

Gamma Ray (Co^{60}) Experiment

The facility used for this experiment is the GSFC Gamma Cell. Gamma Cell is the trade name for a self-contained, self shielded Cobalt 60 source produced by the AEC of Canada. It is a 26,000 curie source, in the form of cylindrical stainless steel "pencils", which contain the Co^{60}, set in a race much like large needle bearings. The outside of the race is surrounded with several inches of lead for shielding. Through the inside of the race, a cylindrical drawer moves up and down preceded and followed by lead slugs for top and bottom shielding. The drawer is electrically operated, controlled either manually, or by a timer circuit built into the machine. The dose rate measured Dec. 1963 was 2×10^6 rads ($FeSO_4 \cdot 7H_2O$)/hr. This has dropped to 1.64×10^6 rads/hr now (July 1, 1965). The temperature in the cell is about 50°C.

Dosimetry is generally accomplished taking the product of time and dose rate, however, the dose rate is checked occasionally using a Cobalt glass dosimeter. Since the dose rate is altered only by the decay of Co^{60}, time is the only variable in achieving different doses.

The instrumentation used for this test consists of a jig with a socket, for holding the device, and a cable of eight leads, 15' in length that run out of the cell to the measurement instrumentation. The instrumentation at the bench includes a switching set, 2 power supplies, an H.P. 425A pico ammeter, and a Dana digital voltmeter. The cable from the jig in the cell is connected to the switching set, which can switch the device leads into three different test configurations. The first position switches the 8 leads of the microcircuit to 8 binding posts. Operating conditions during radiation can be patched into these terminals. The second position switches the device to a modified gate threshold voltage measurement shown in a simplified schematic below (Figure I.1).

In Figure I.1 gate 7 voltage is increased (negatively) until the desired I_D is indicated on the current meter. Three currents were chosen for I_D, 10 μa, 50 μa and 100 μa. The gate voltages required to achieve these currents are recorded and these steps are repeated for each gate.

The third position on the switching set measures drain to source leakage. This is achieved by grounding the gate and switching a pico ammeter and power supply from drain to drain and the ground from source to source. This position, however, was not used in these tests.

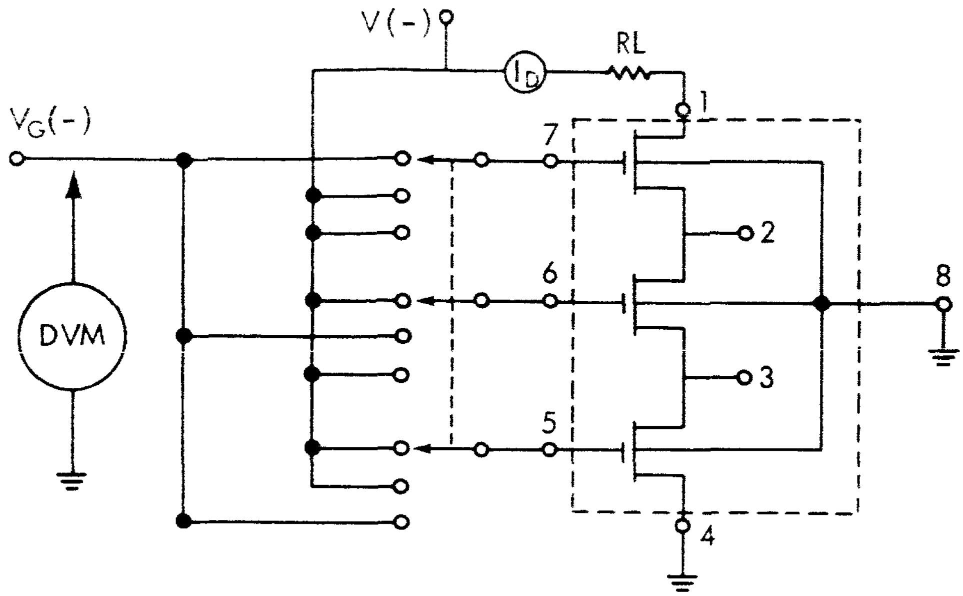

Figure 1.1. Gate Threshold Section of Original Test Circuit.

The experiment was run in the following manner: Initial data were taken. The device was exposed to the radiation. Post exposure data were taken. The device was re-exposed, and so on until the end of the run. This procedure yields a parameter versus radiation dose curve. Nine (9) SC1128's were exposed. Three (3) were operated with a supply of 10 v and an I_D of 90 μa, five were operated with a supply of 20 v and an I_D of 180 μa and one was operated at 6 v supply until threshold reached 6 v then at 10 v until threshold reached 8.6 v and 20 v until the end of the test. The drain currents were 54, 90, and 180 μa. Devices from this experiment were labeled A_1, A_2, . . . A_n.

2 Mev Electron Experiment

One of the Grace Research Laboratories' facilities is a vertical 2 Mev Van de Graaff accelerator capable of a beam current of 200 microamps. The beam can be scanned some 18 inches at the face of the scanning horn at a 400 cycle per second rate. A variable speed conveyer is available to carry samples through the beam. Goddard has purchased time on this machine, some of which was used for this experiment.

Dosimetry was achieved through the use of a Faraday cup connected to an Elcor current integrator. The total charge to indicate the desired dose is calculated. This value is set on the Elcor register, and an indicator lights when the register returns to zero, which indicates that the set charge has been accumulated. When the light comes on, the operator turns the beam off.

The experiment at Grace Laboratories was somewhat different from the Co^{60} work in that a new test circuit suggested by Roland Van Allen, Flight Data Systems Branch, was used to measure gate threshold voltage. A simplified diagram is shown below (Figure I.2).

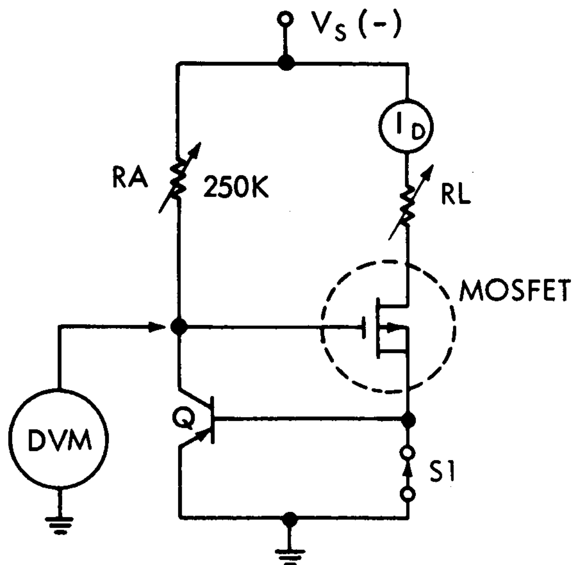

Figure I.2. Gate Threshold Test Circuit

RL in this circuit is adjusted for an I_D of 100 μa with S1 closed. Vs is the desired bias during irradiation which appears at the gate of the MOSFET through RA. To take a measurement S1 is opened, drain current flows through the transistor (Q) base causing the collector voltage to pull towards ground. Since the gate of the MOSFET is tied to the collector of Q, the MOSFET starts to turn off until an equilibrium point is reached. This point is chosen as 10 μa I_D and is adjusted by RA. This holds until the supply voltage less the drop across RA is not high enough to turn on the MOSFET. The remedy for this ailment is to decrease RA. The primary advantage of this circuit is that the leads of the device under test are not switched and, therefore, less likely to be damaged by electrostatic discharge. The actual circuit does switch between gates but this is done with S1 closed thus electrostatic discharge is still not a problem. Gate threshold was the only parameter measured for this electron experiment. It was measured on each gate of each device irradiated.

The jig holding the MOSFET was taped to a slotted aluminum plate which was designed to hold the Faraday cup in the electron beam. The cup and jig next to each other in the line of scan so that both received the same dose rate from the scanned beam as the beam scans the slotted plate.

Five SC1129's operated at 6.6VG and 100 μa I_D during exposure were tested, as were nine SC1128's, three of which were operated 20 VG, another three at 15 VG and another three at 10 VG. All were operated at 100 μa drain current. The devices used in this experiment were marked B1, B2, B3, etc.

22 Mev Proton Experiment

The latest work done on these integrated circuits by the Radiation Effects Group entailed the use of 22 Mev protons from a cyclotron at Oak Ridge National Laboratories (ORNL). Twelve SC1128 circuits and three SC1129 circuits were exposed. The SC1128's were tagged C1, C2, . . . C12; the SC1129's were tagged C13, C14, C15. The exposures were conducted in the following way. The devices were tested with a 575 curve tracer. A 1K, 0.1% resistor was connected from the base step generator output to ground, (with the generator set for constant current steps, this gives 1 volt/step for 1 ma/step setting on the generator) and an adjustable power supply was connected in series with the step generator and the gate of the MOSFET. This system provides an offset voltage with the step generator so that many steps can be displayed giving better resolution to the display. Figure I.3 illustrates the scheme.

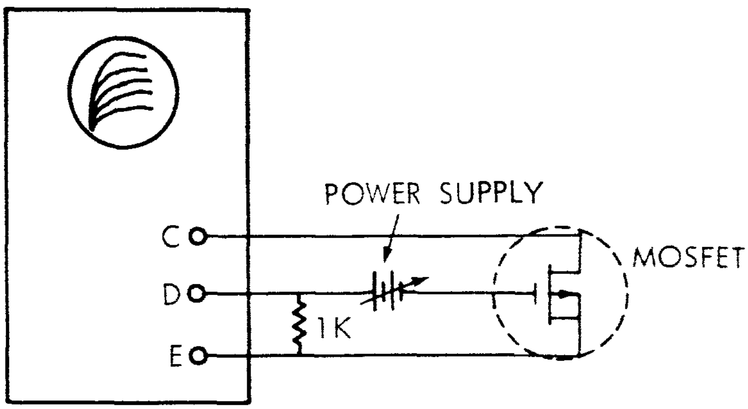

Figure I.3. Using a 575 Curve Tracer To Display MOSFET Drain Characteristics

If a power supply were not used in series with the gate, most of the steps from the 575 would be used in achieving threshold and the "voltage spacing" of the steps (about 0.5 v to do this) would be too wide to give a large family of drain curves.

Photographs of the VD-ID display of each of the three transistors in each microcircuit were taken before and after exposure. At selected intervals during exposure, the beam was interrupted, the gate threshold voltage was measured, (using the same circuit used in the electron experiment conducted at W. R. Grace Research Center) and the data were recorded.

Dosimetry was provided by ORNL. It consisted of an ion chamber, calibrated at various beam currents using a Faraday cup. After calibration, ion chamber charge (integrated current) was calculated for each dose desired. An Elcor current integrator was set to the calculated charge, and the beam was shut down by the Elcor (closing a shutter) when the set charge was accumulated.

The facilities at ORNL included 15' of work bench space and adequate power outlets. An adjustable height table about 2' square is available in the target room for holding samples in the beam. It is about a 30' run from the target area to the work benches. We used 50' cables for in situ measurements. Communications between the cyclotron operator and the experimenter are via head set.

In the experimenter's area, there is a pushbutton control for the opening and closing of the shutter which intercepts the beam when in the closed position. One item that would have been a real asset is a device to remotely locate the units under test in the cyclotron beam. The sort of thing I mean is a motor driven disc with the units to be tested on its circumference. With the beam aimed at one spot on the circumference, devices could be located in the beam by turning the disc.

Results

All of the data are presented here in the form of graphs at the end of the report. Typical curves are injected into the text of this report to illustrate a point without the reader having to flip back and forth between text and graph.

The graphs are plots of gate threshold voltage vs. dose. Gate threshold voltage is that gate voltage at which conduction between source and drain just begins in enhancement MOSFETS. In the case of the illustrations, the gate threshold voltage is normalized to its pre-irradiated value. There are also graphs of the drain current vs. gate voltage before and after exposure to protons. The plots of gate threshold voltage vs. dose are the average of the three gates in each unit in any event the gate voltages were within 0.1 volt for any given unit.

The curves for units A1 through A10 (exposed to Co^{60} gammas) are Figures IV.1 through IV.9 and Figure II.1 below. They are plots of gate voltage vs. dose at three different drain currents; namely, 10 μa, 50 μa and 100 μa. The spacing between the curves in an indicator of the transconductance (gm) = ratio of the change in drain current to the change in gate voltage ($\partial Id/\partial Vg$). These curves tending to diverge indicates an increase in gm, whereas, their tending to converge indicates a decrease in gm Figure II.1 is representative of this group illustrating both tendencies along the curve, but there is no strong tendency toward either convergence or divergence. The curves do indicate the strong dependence of gate threshold voltage on dose.

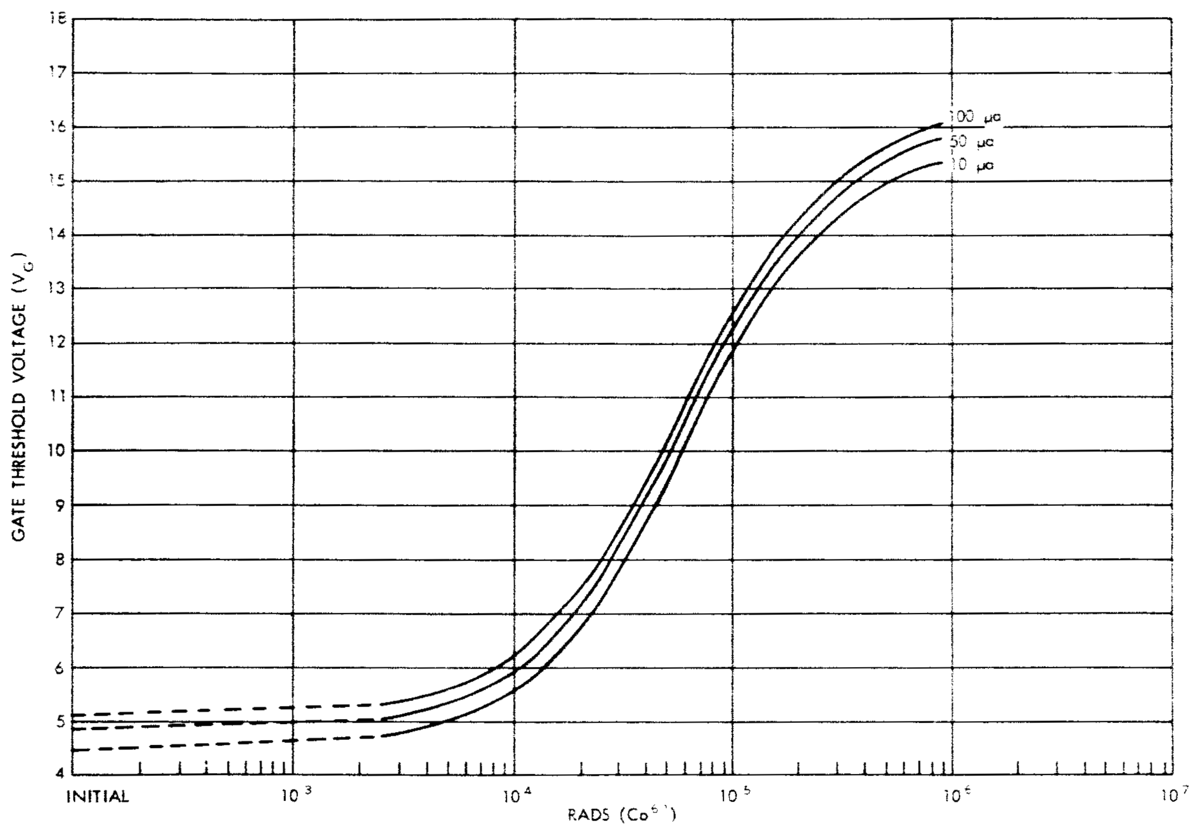

Figure II.1. Unit A3 20 Volts Gate Bias 180 μa Drain Current During Exposure.

For our purpose, gate threshold voltage is defined at a drain current of 10 μa. These curves demonstrate another interesting reaction of the device to the radiation, that is, the rate of gate threshold change with radiation is influenced by the operating voltage of the gate during exposure. This is clearly illustrated in Figures II.2 and II.3.

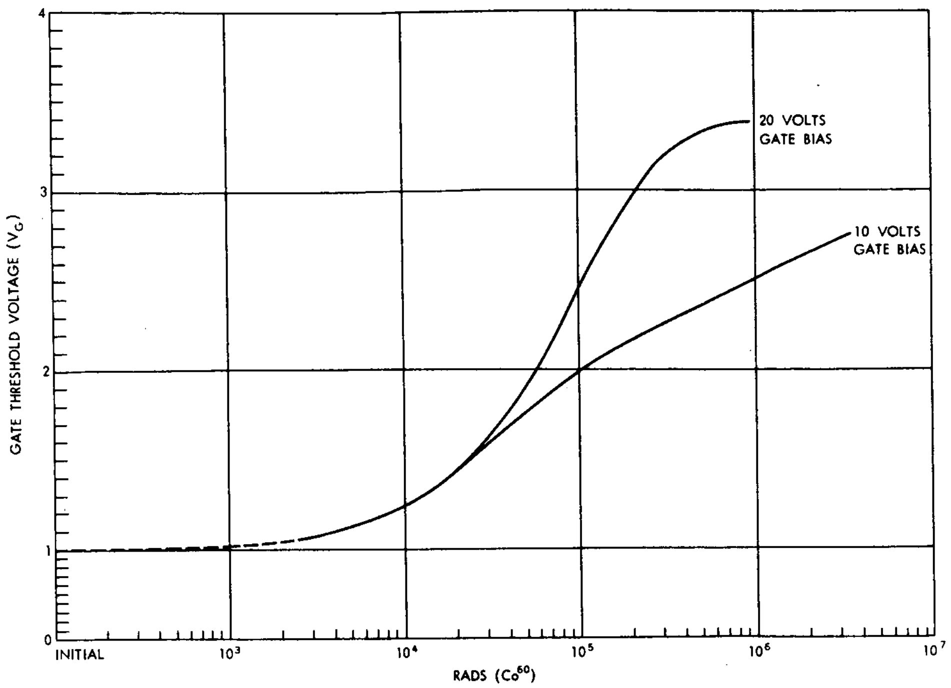

Figure II.2. Gate Threshold vs. Dose with Two Biases.

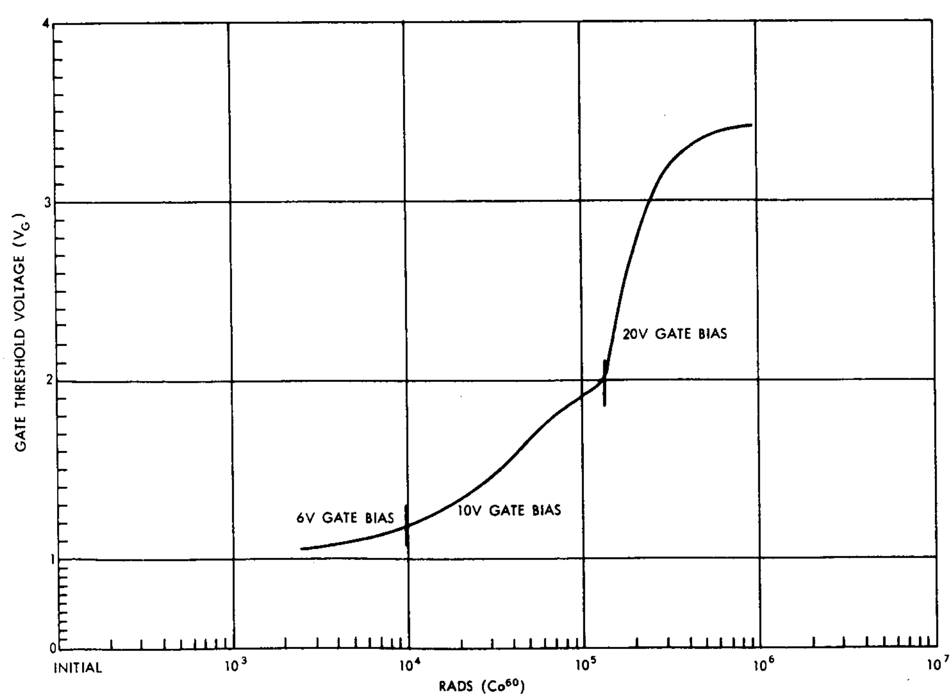

Figure II.3. Gate Threshold vs. Dose with Bias Change During Exposure.

The graphs of devices with a B prefix are data taken, using a 2 Mev electron source. These data (Figure IV.10 through IV.23) are summarized in Figure II.4 which is a composite of typical curves from this experiment. There are four groups in these data, one for each of the following gate voltage during exposure: 6.6 v, 10 v, 15 v, and 20 v. Two dependency relationships are noted. The first is the increase in gate threshold with dose. These curves are very similar to the Co^{60} data. If one were to assume 2×10^7 electrons (2 Mev)/rad as a conversion factor, this electron data would look like Co^{60} data. The second effect is the dependence of damage rate on gate bias during exposure. This dependence is also similar to the Co^{60} data as shown in Figure II.4. All in all, the results of the electron exposures yielded no surprises in light of the Co^{60} information.

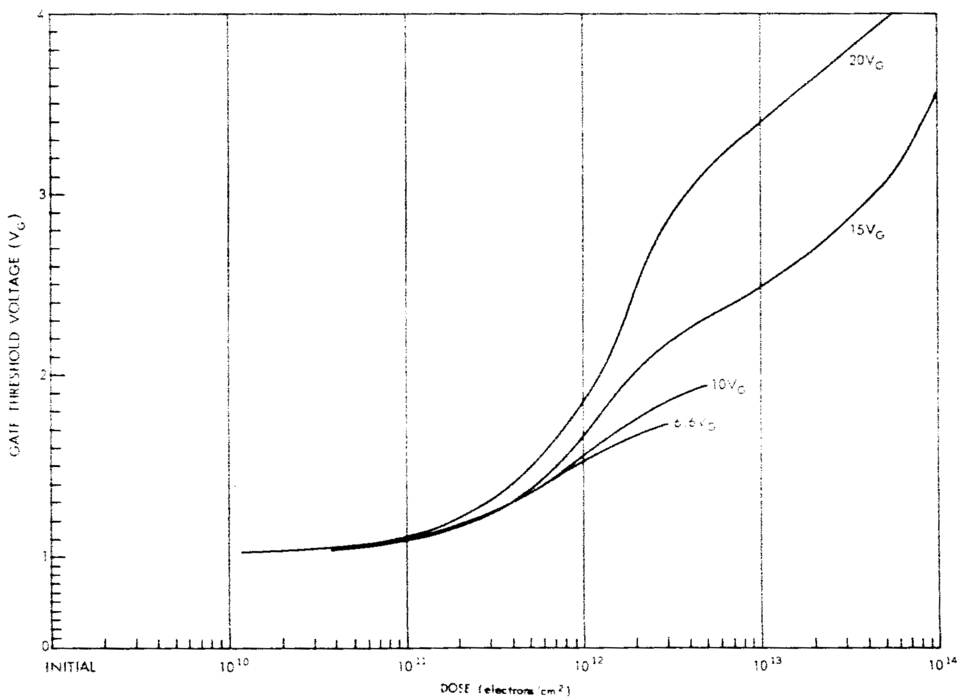

Figure II.4. Typical Normalized Gate Threshold Voltage vs Dose With Gate Bias During Exposure Indicated.

The graphs of the C prefix units are the proton data. One set of graphs (Figure IV.24 through IV.37) is the usual (for this report) gate threshold voltage vs. dose plot. The gate threshold voltage does increase significantly with dose. If a conversion factor of 5×10^6 protons (22 Mev)/rad then these graphs would also appear as Co^{60} data. A dependence of gate threshold voltage damage rate on gate bias is also noted and illustrated in Figure II.5.

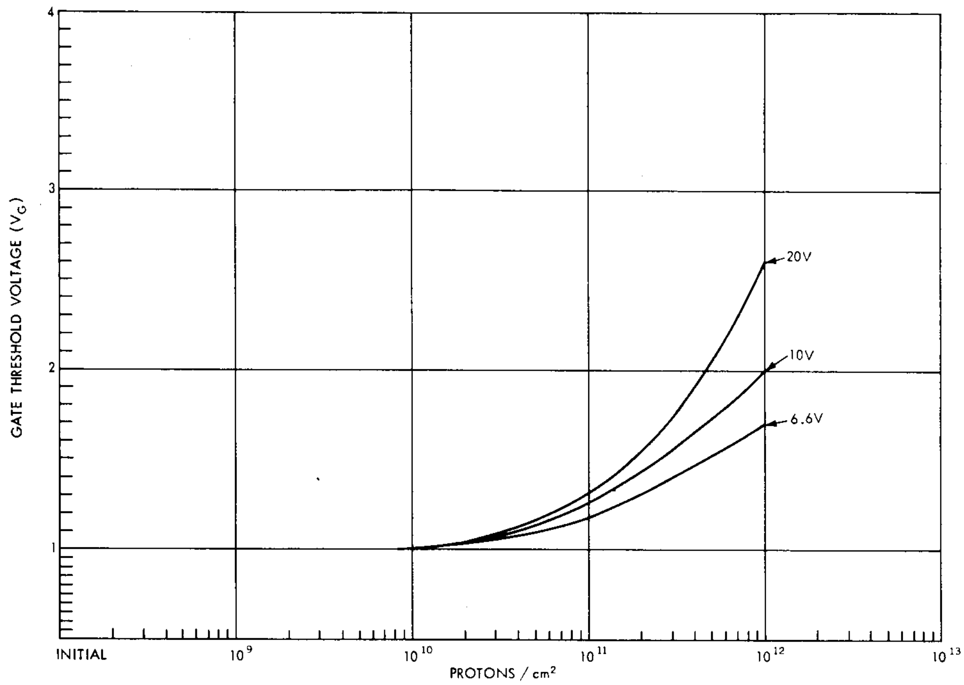

Figure II.5. Typical Normalized Gate Threshold Voltage vs Proton Dose

Other data taken are photographs of the drain characteristics using a 575 curve tracer as mentioned before. These data gave sufficient information to plot the graphs of drain current (Id) vs. gate voltage (Vg) with constant drain voltage (Vd), before and after exposure to 22 Mev. protons. The transconductance of these devices can be obtained by measuring the slope of the curve at a given drain current. I chose, quite arbitrarily, 0.7 ma as that current. The results of this endeavour are shown in Table II.1.

TABLE II.1 Transconductance (gm, taken from I/g-Id plot)

Unit & Gate	gm (μmho)		gm_n	Unit & Gate	gm (μmho)		gm_n
	Before	After			Before	After	
C1-1	714	648	0.908	C7-1	631	514	0.815
C1-2	700	609	0.870	C8-1	555	642	1.157
C1-3	619	654	1.057	C9-1	583	564	0.967
C2-1	714	593	0.831	C10-1	522	573	1.098
C2-2	722	625	0.866	C11-1	660	404	0.612
C3-1	493	546	1.108	C13-1	619	619	1.000
C4-1	473	603	1.275	C14-1	707	578	0.818
C5-1	560	526	0.939	C15-1	648	686	1.059
C6-1	574	556	0.969	Avg.	617	584	0.962

gm_n = gm after ÷ gm before

From this table, 7 units either remained the same or increased and 10 units decreased.

CONCLUSIONS

The results of these experiments on p channel enhancement MOSFETS bring me to the following conclusions:

1. Ionizing radiation causes an increase in gate threshold voltage.

2. The rate of change of threshold voltage with radiation is influenced by the gate bias during exposure. In this case an increase in negative bias on the gate during exposure increases the rate at which the gate threshold voltage changes.

3. Transconductance changes with ionizing radiation, however, the direction of its change is unpredictable. One may not say that the gm of one device will continue to decrease even after it has decreased from previous radiation. One should remember, however, that this conclusion is based in part on the measurement of gm via the spaces between the 10, 50, and 100 μa curves of the Co^{60} data. The accuracy of determining gm in this fashion can be legitimately questioned.

My first conclusion is in agreement with at least one other investigator in the field (Reference 2).

REFERENCES

1. "Imp D & E (AIMP) PFM Encoding System interface document" March 1965, NASA X-631-65-104.

2. "Radiation effects in Metal-Oxide-Semiconductor Transistors." Raymond, Steele and Chang. IEEE Transactions on Nuclear Science, Vol. NS12 number 1, pp 457 - 463, February 1965.

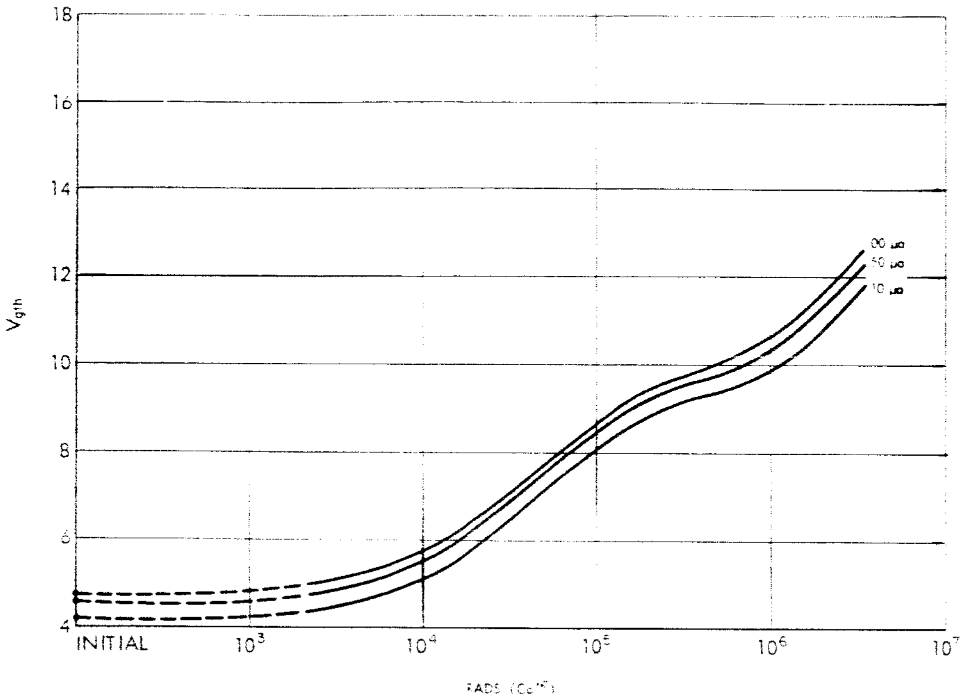

Figure IV.1. Unit A1 10 Volts Gate Bias 90 μa Drain Current During Exposure.

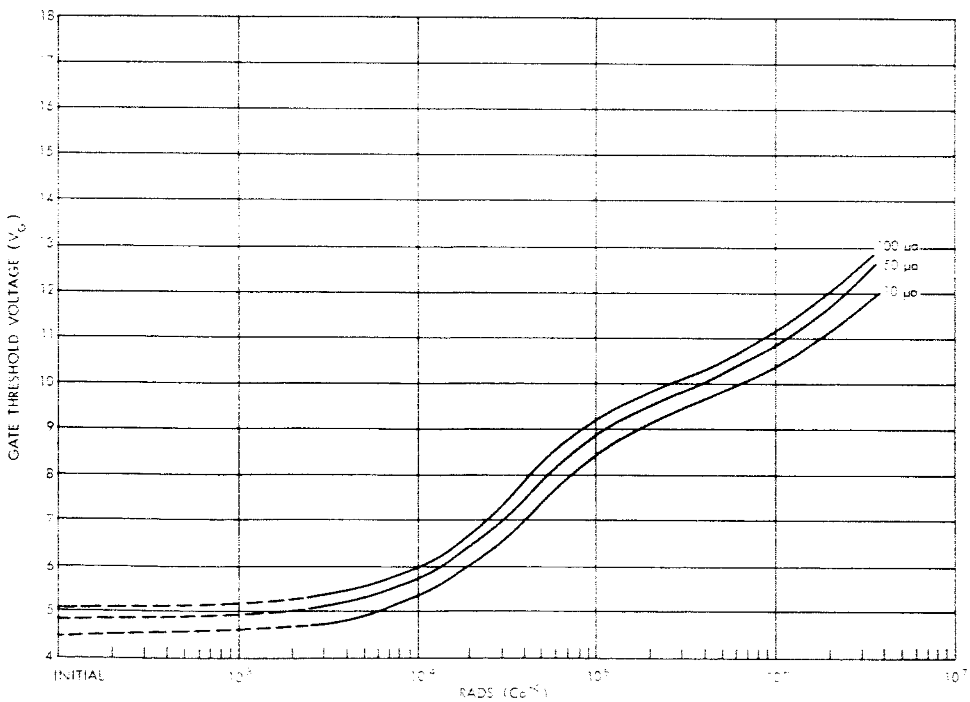

Figure IV.2. Unit A6 10 Volts Gate Bias 90 μa Drain Current During Exposure.

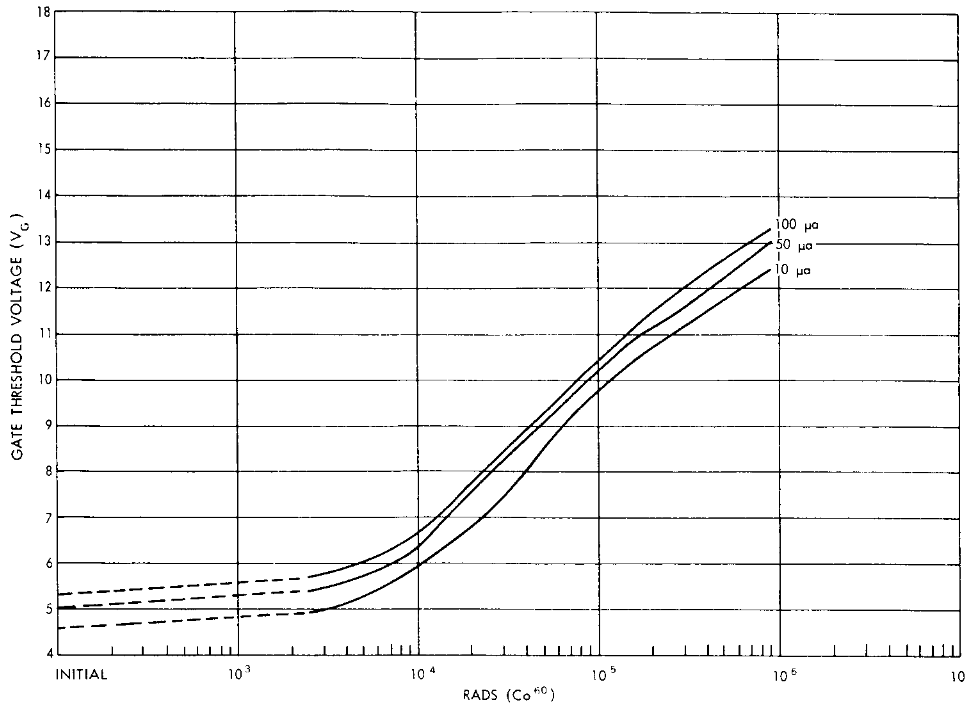

Figure IV.3. Unit A7 10 Volts Gate Bias 90 μa Drain Current During Exposure.

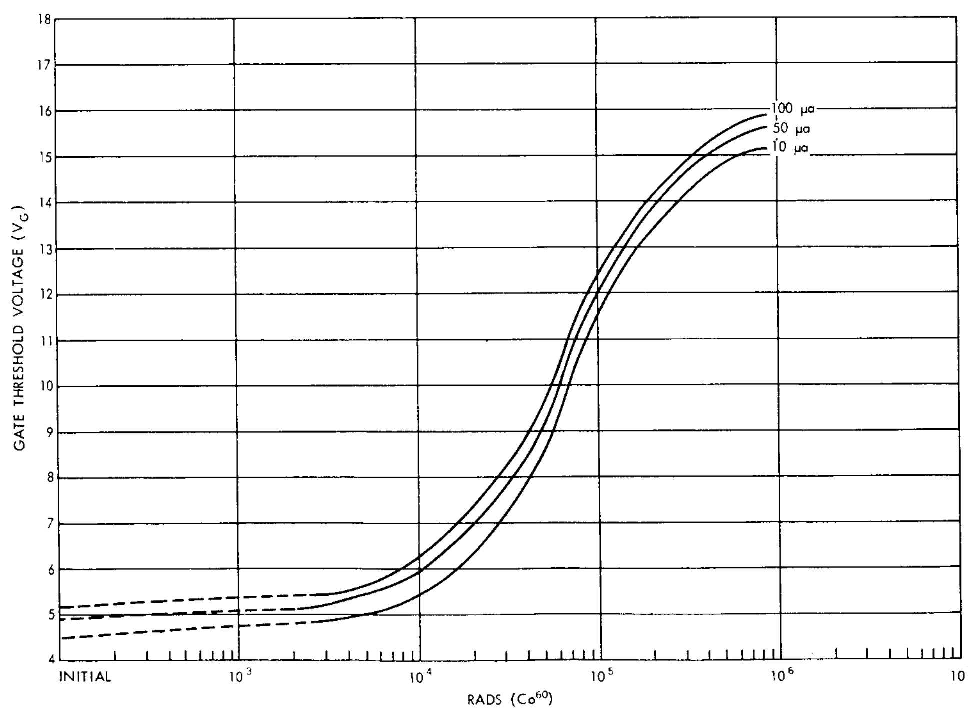

Figure IV.4. Unit A2 20 Volts Gate Bias & 180 μa Drain Current During Exposure.

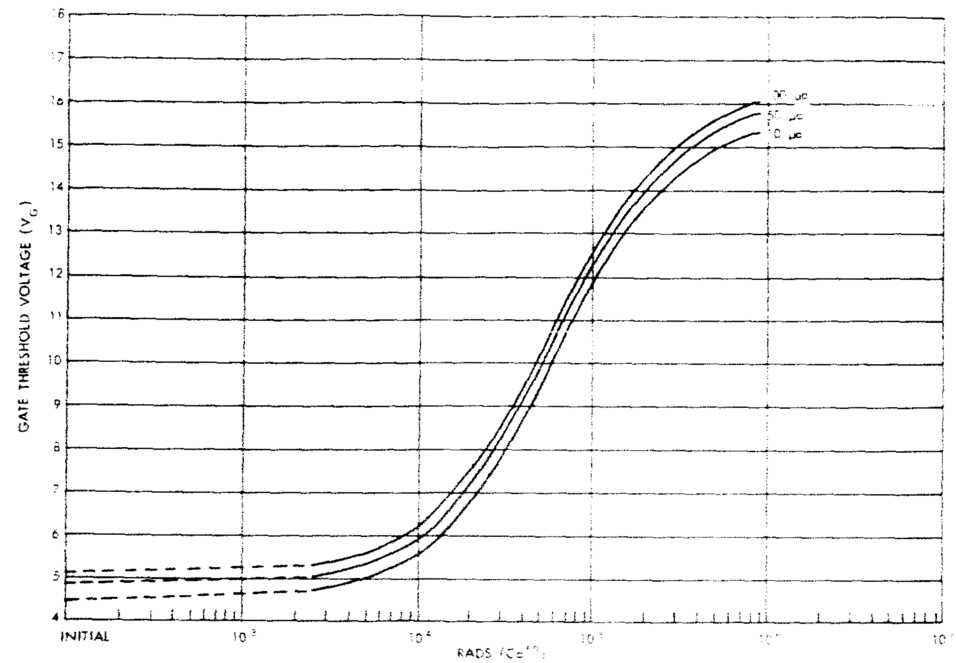

Figure IV.5 Unit A3 20 Volts Gate Bias 180 μa Drain Current During Exposure.

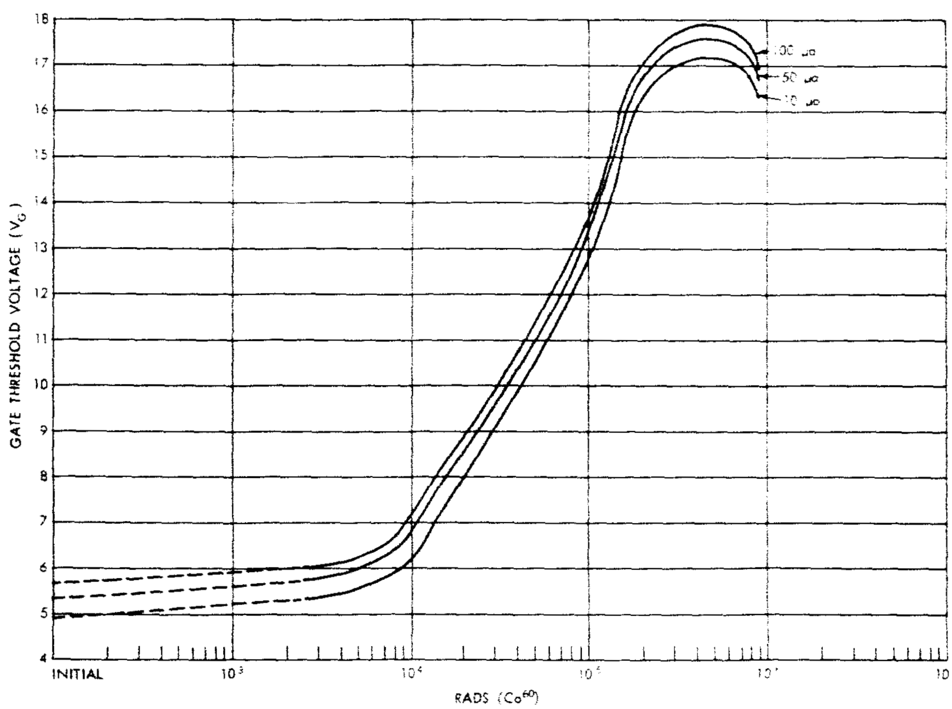

Figure IV.6. Unit A4 20 Volts Gate Bias & 180 μa Drain Current During Exposure.

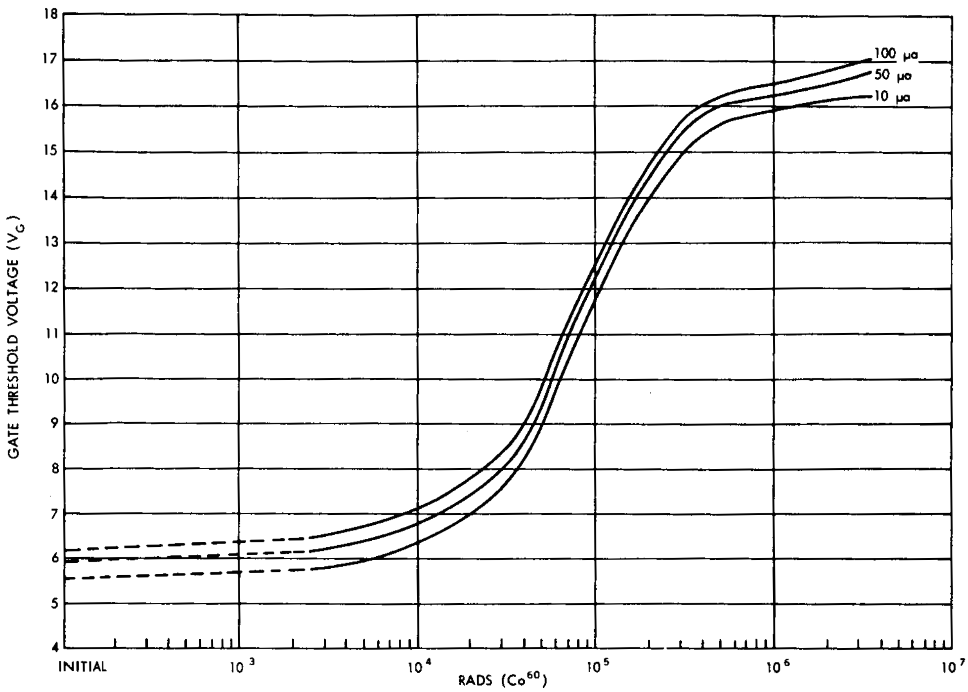

Figure IV.7. Unit A5 20 Volts Gate Bias & 180 μa Drain Current During Exposure.

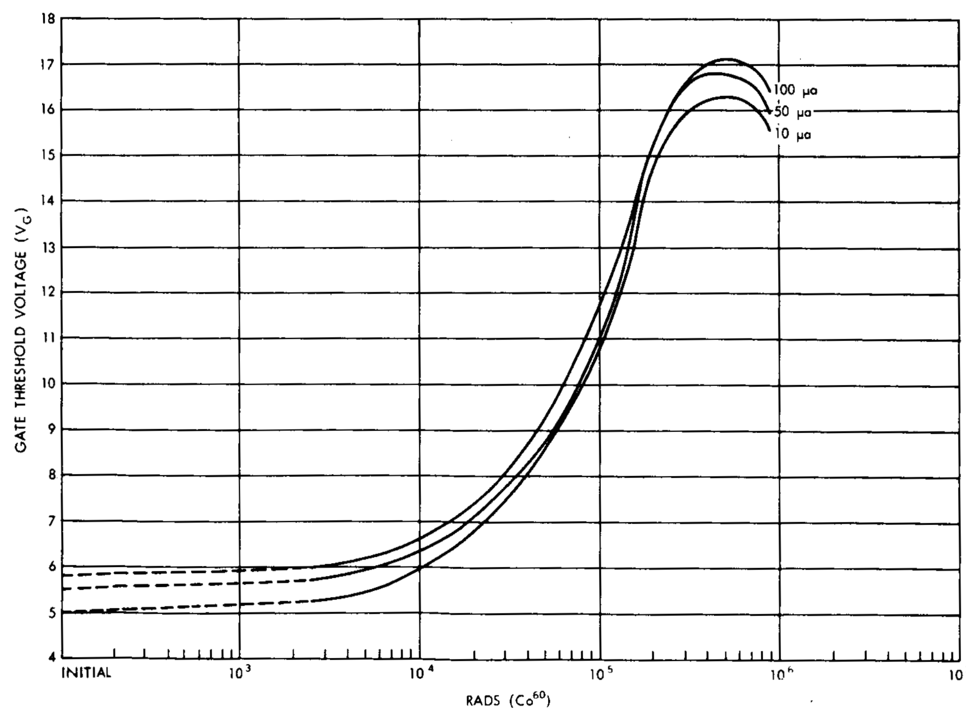

Figure IV.8. Unit A10 20 Volts Gate Bias 180 μa Drain Current During Exposure.

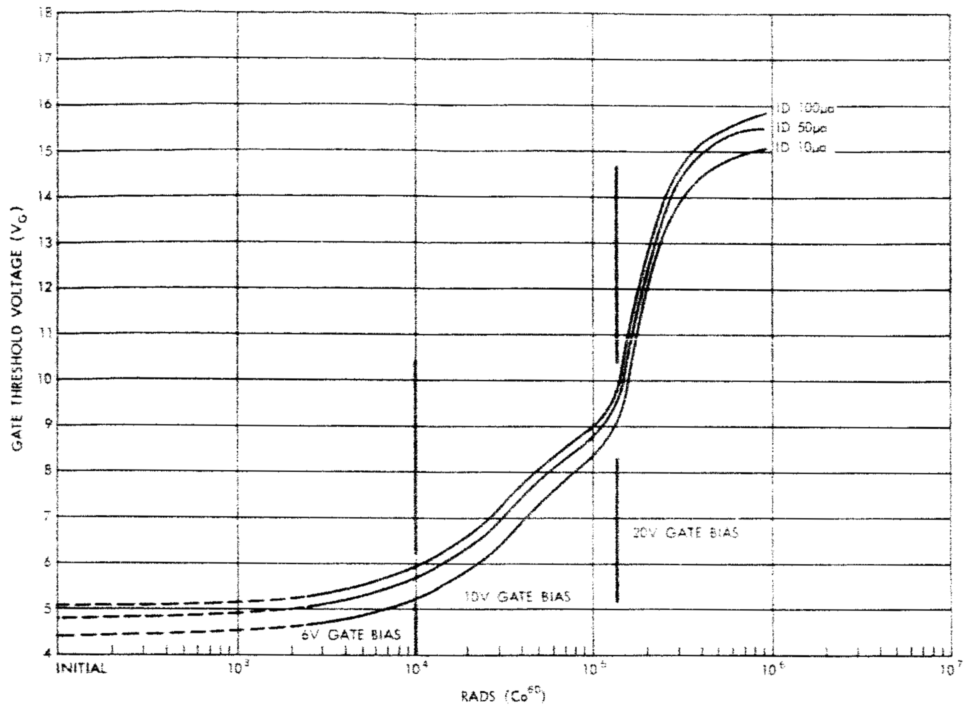

Figure IV.9. Unit A8 Voltage by Different Portions of Curve Indicate Bias During Exposure.

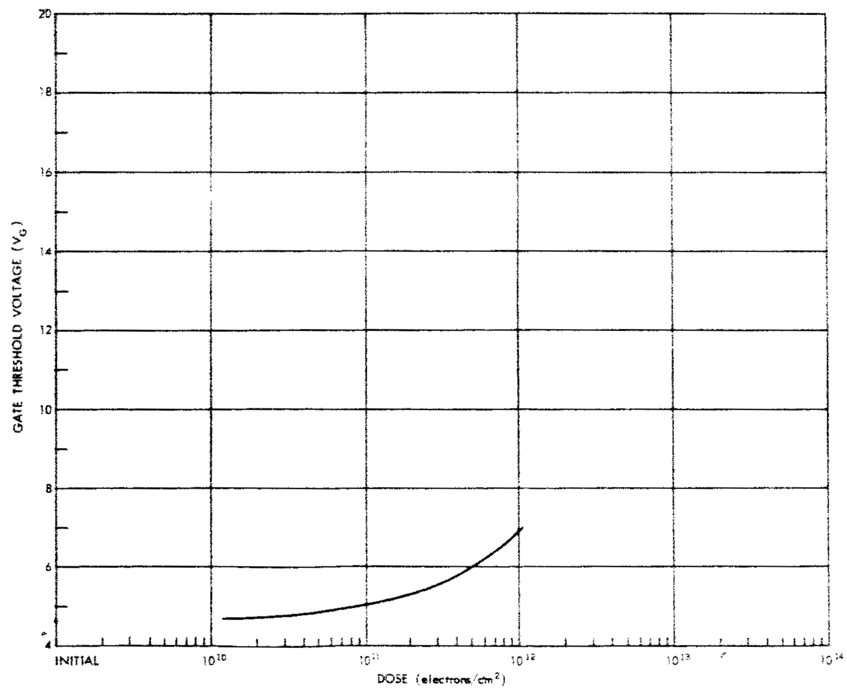

Figure IV.10. Unit B2 (SC1129) 6.5 V Gate Bias During Exposure 100 μa Drain Current During Exposure.

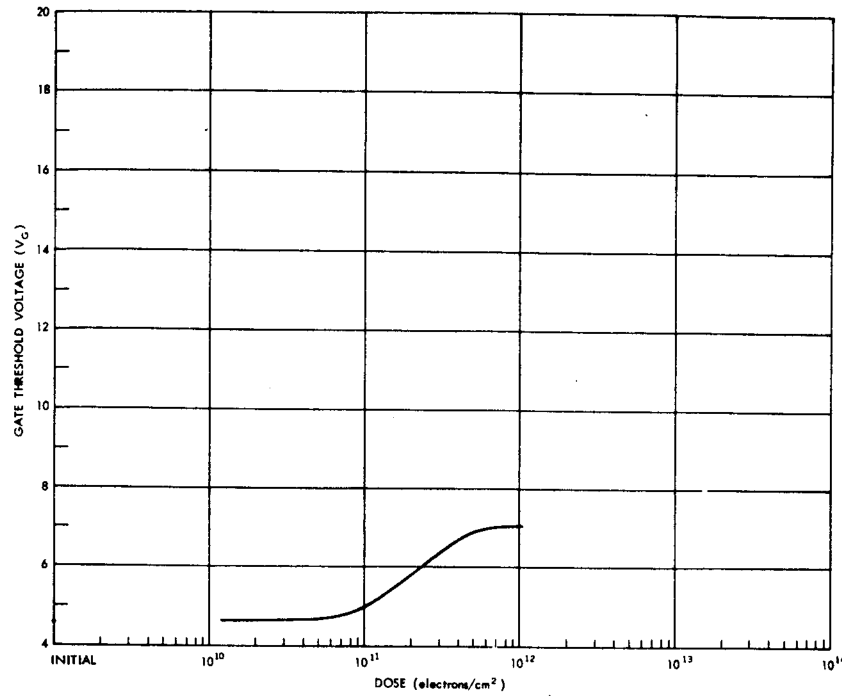

Figure IV.11. Unit B3 (SC1129) 6.5 V Gate Bias During Exposure 100 μa Drain Current During Exposure.

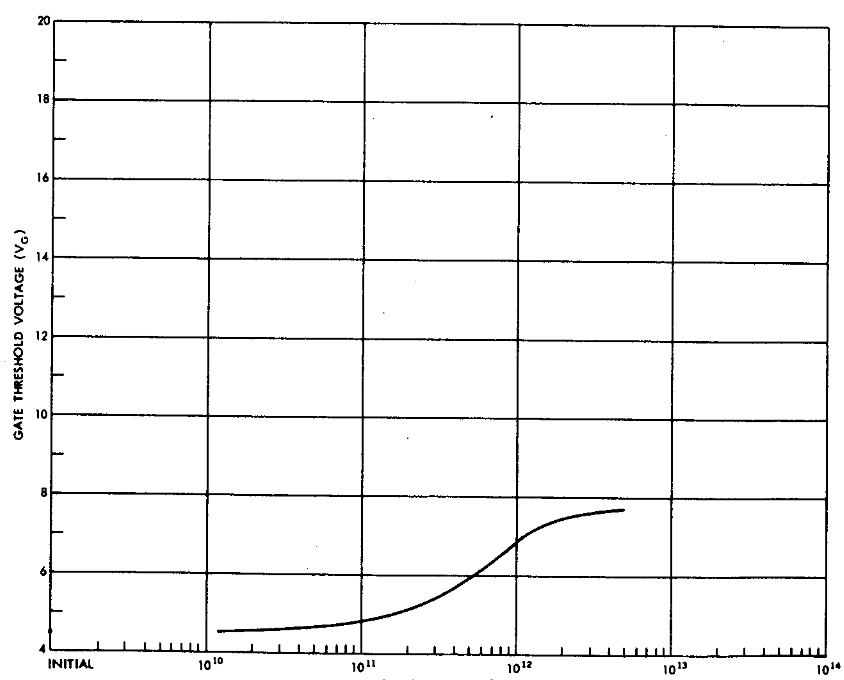

Figure IV.12. Unit B4 (SC1129) 6.5 V Gate Bias During Exposure 100 μa Drain Current During Exposure.

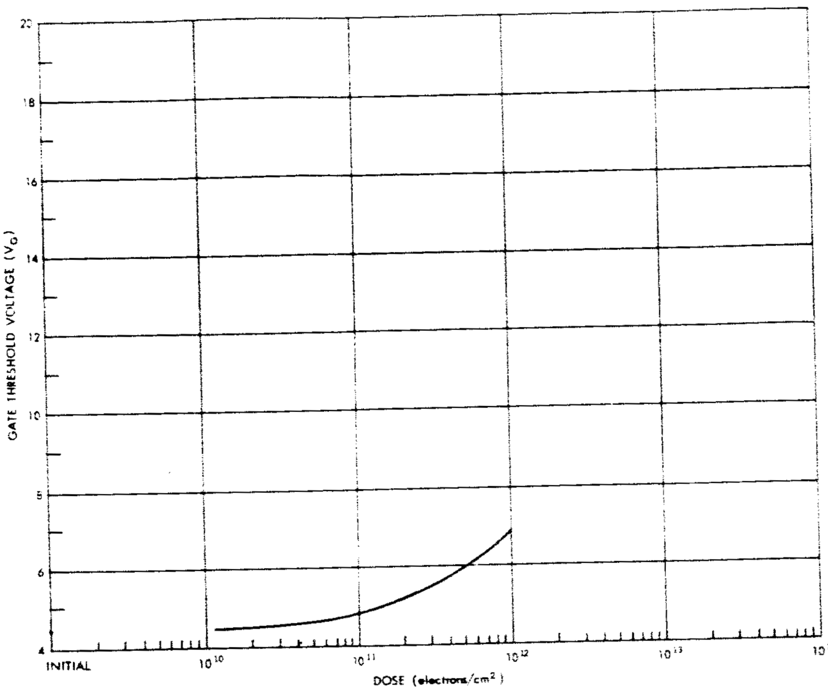

Figure IV.13. Unit B5 (SC1129) 6.5 V Gate Bias During Exposure
100 μa Drain Current During Exposure

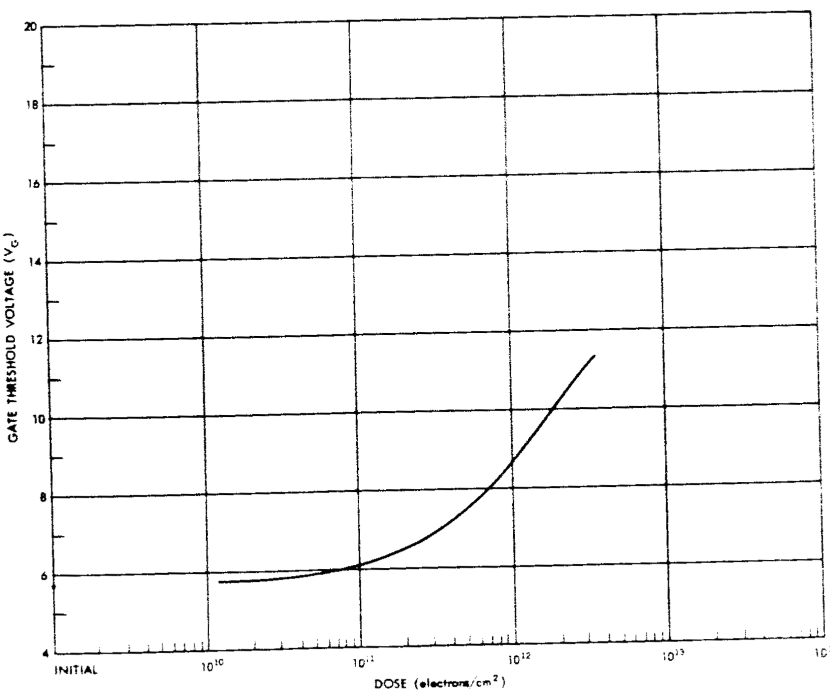

Figure IV.14. Unit B13 10V Gate Bias During Exposure
100 μa Drain Current During Exposure.

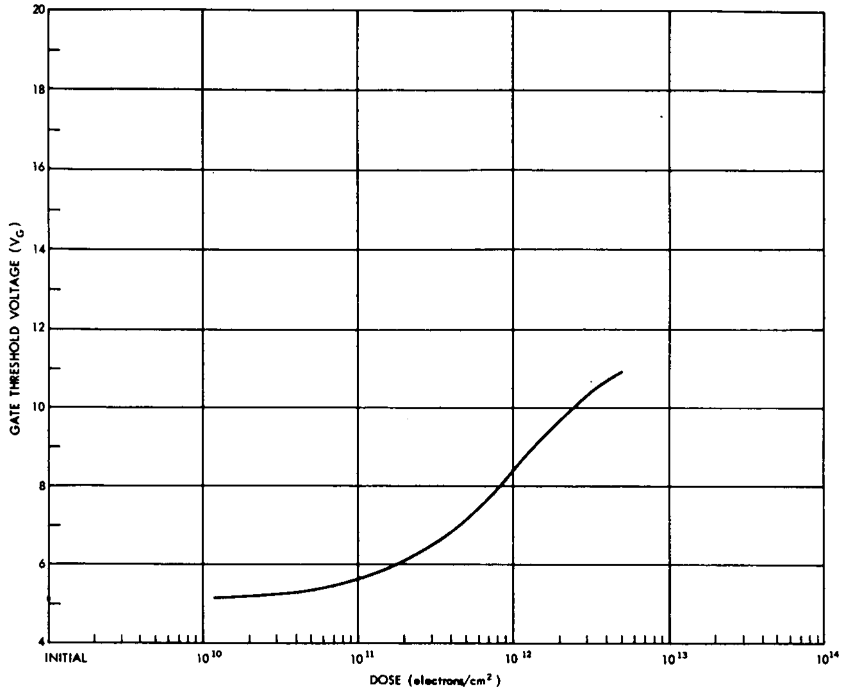

Figure IV.15. Unit B14 10 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

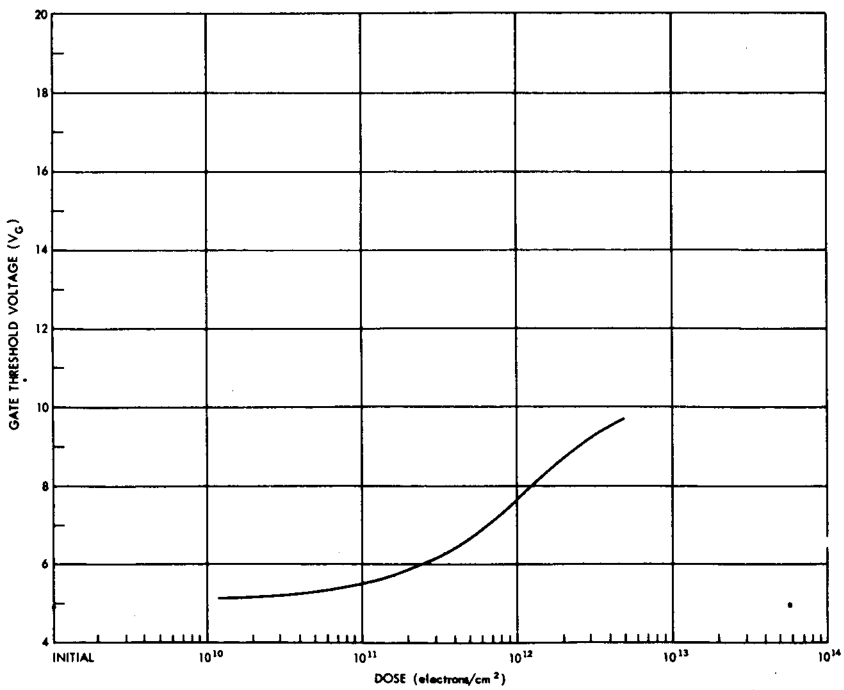

Figure IV.16. Unit B15 10 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

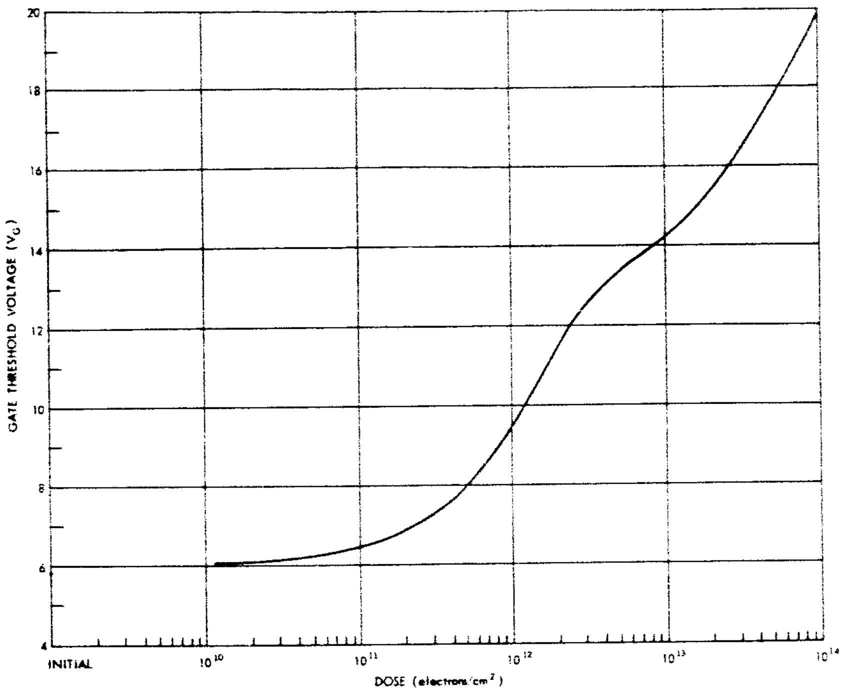

Figure IV.17. Unit B10 15 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

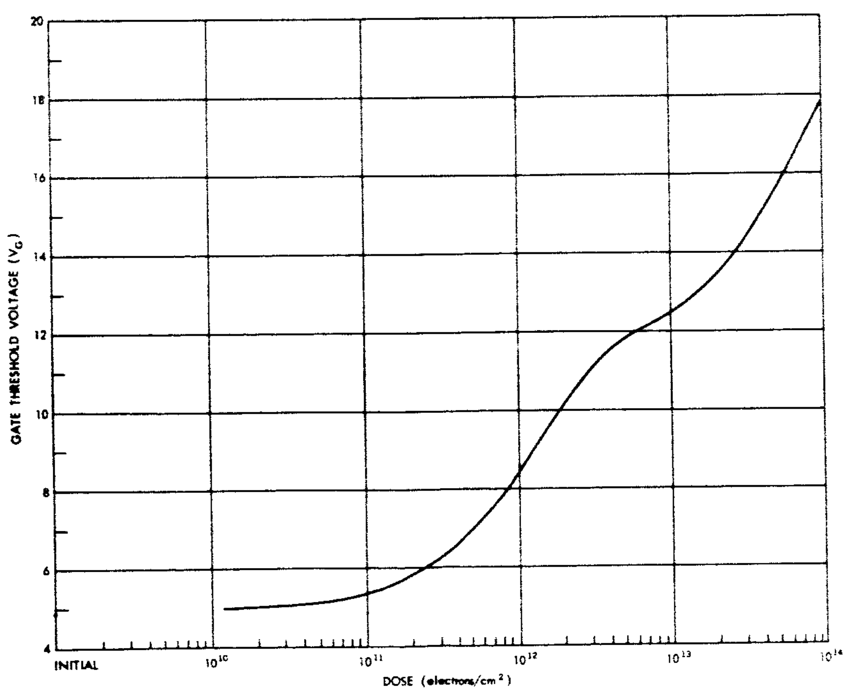

Figure IV.18. Unit B11 15 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

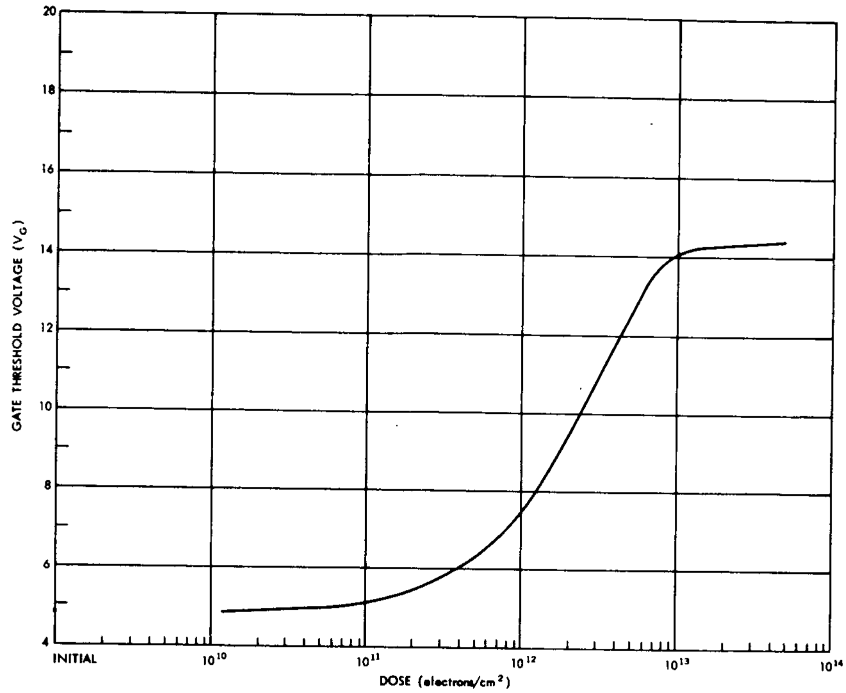

Figure IV.19. Unit B12 15 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

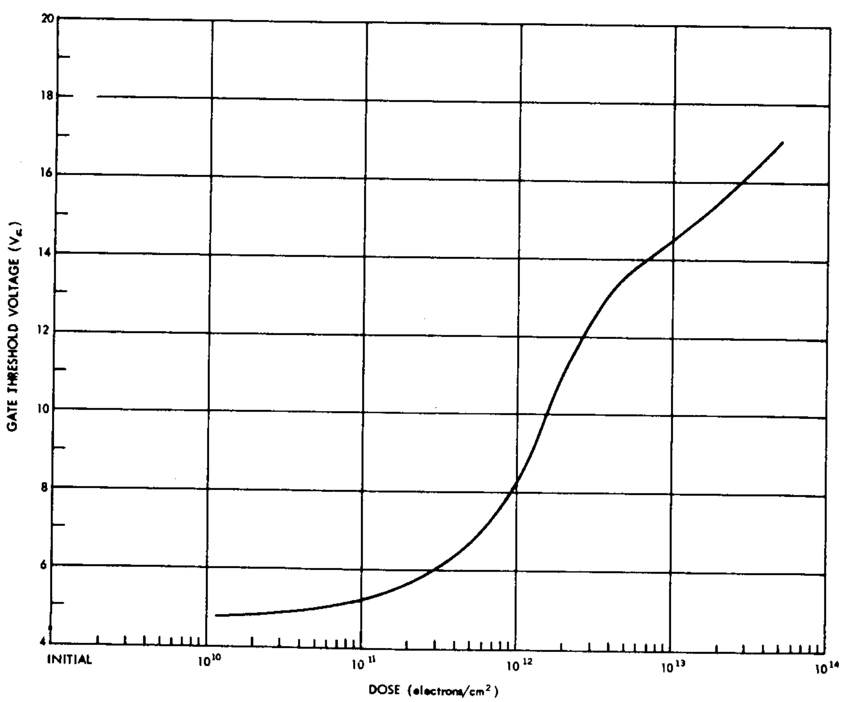

Figure IV.20. Unit B1 (SC1129) 20 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

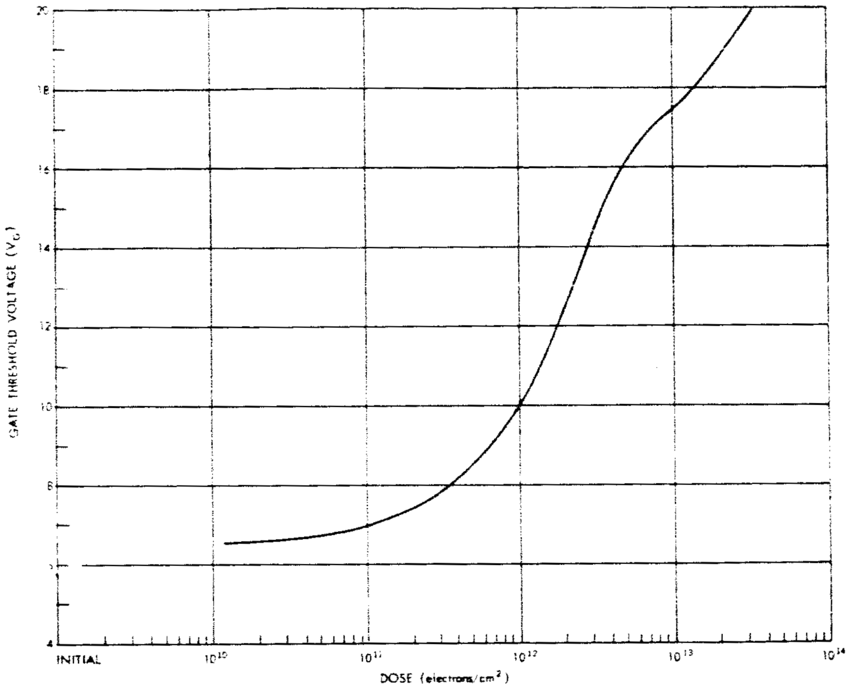

Figure IV.21. Unit B6 20 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

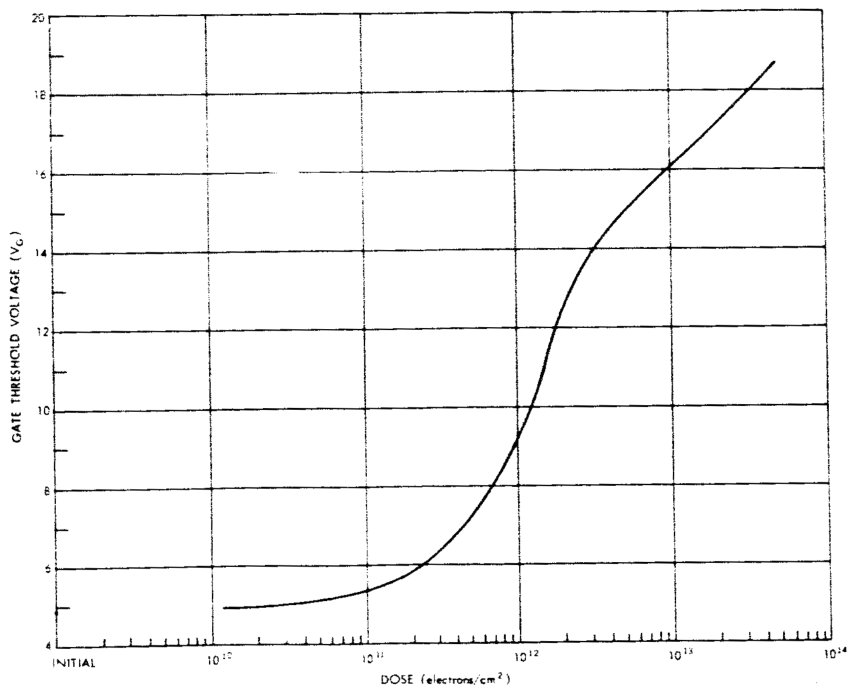

Figure IV.22. Unit B7 20 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

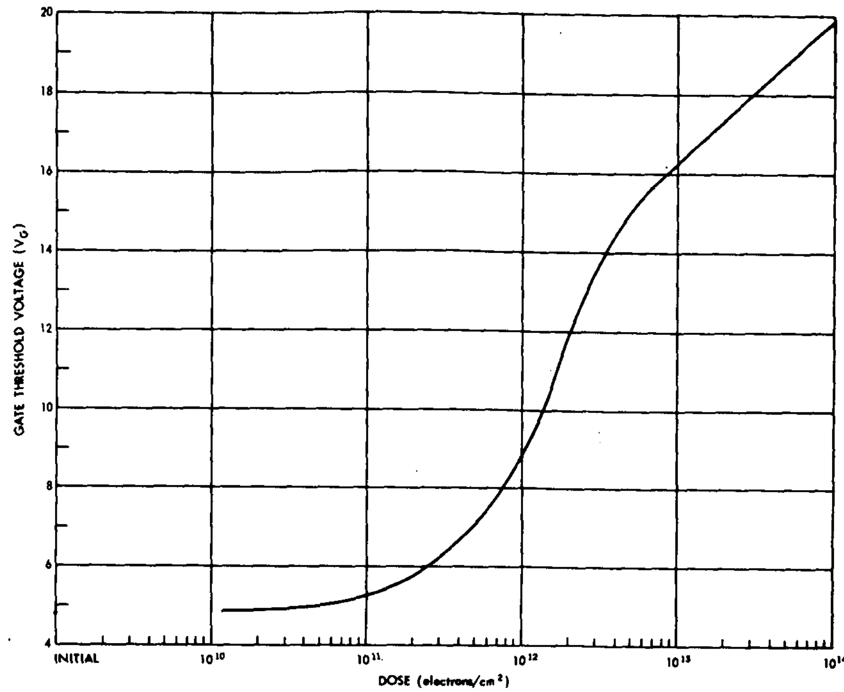

Figure IV.23. Unit B8 20 V Gate Bias During Exposure
100 μa Drain Current During Exposure.

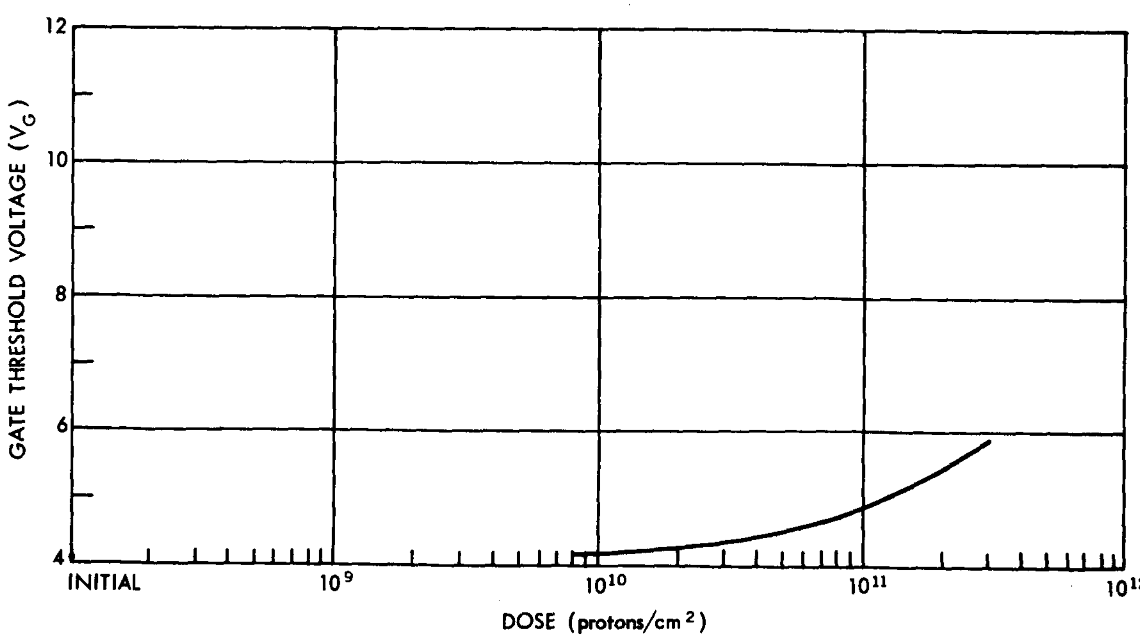

Figure IV.24. Unit C14 (SC1129) −6.6 Volts Gate Bias and
100 μa Drain Current During Exposure.

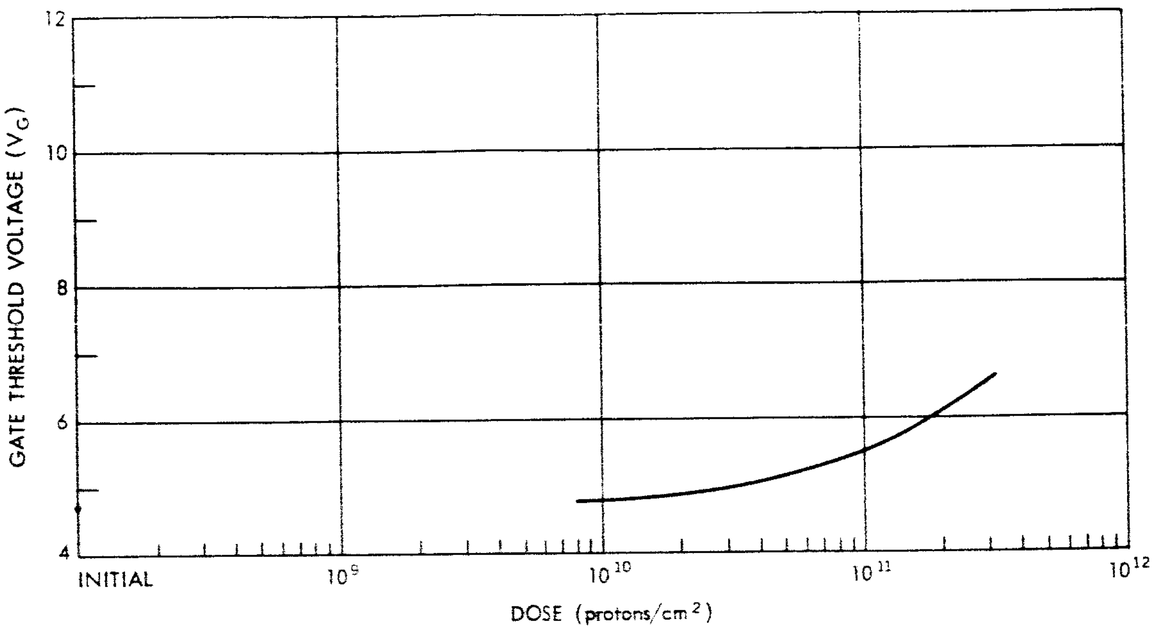

Figure IV.25. Unit C15 (SC1129) −6.6 Volts Gate Bias and 100 μa Drain Current During Exposure

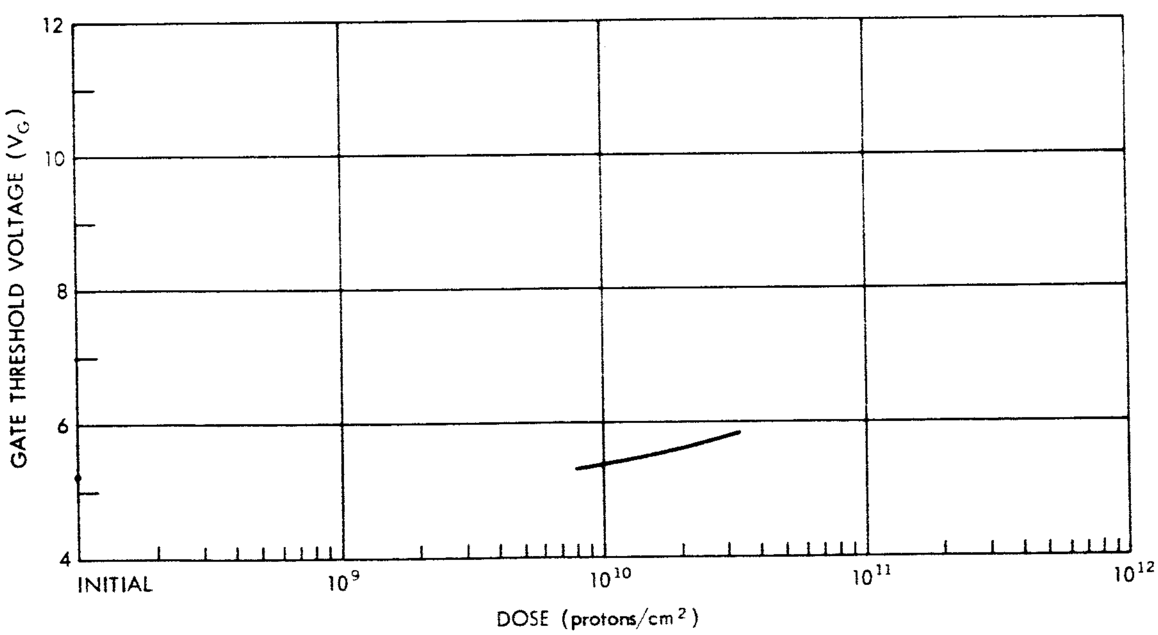

Figure IV.26. Unit C11 (SC1128) −6.6 Volts Gate Bias and 100 μa Drain Current During Exposure

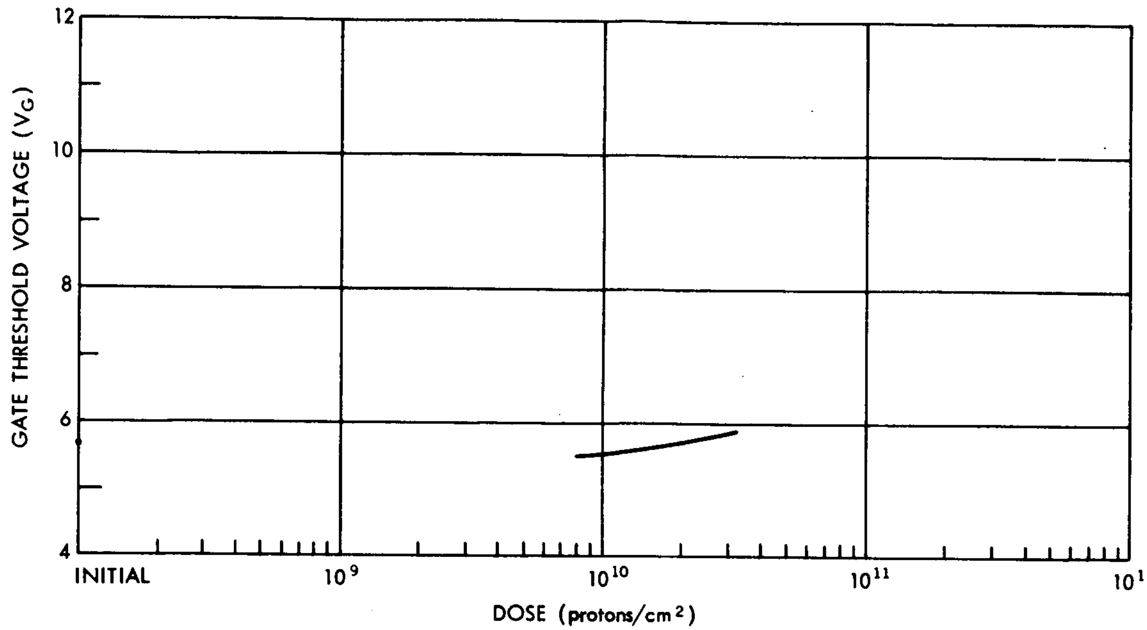

Figure IV.27. Unit C10 (SC1128) −6.6 Volts Gate Bias and 100 μa Drain Current During Exposure.

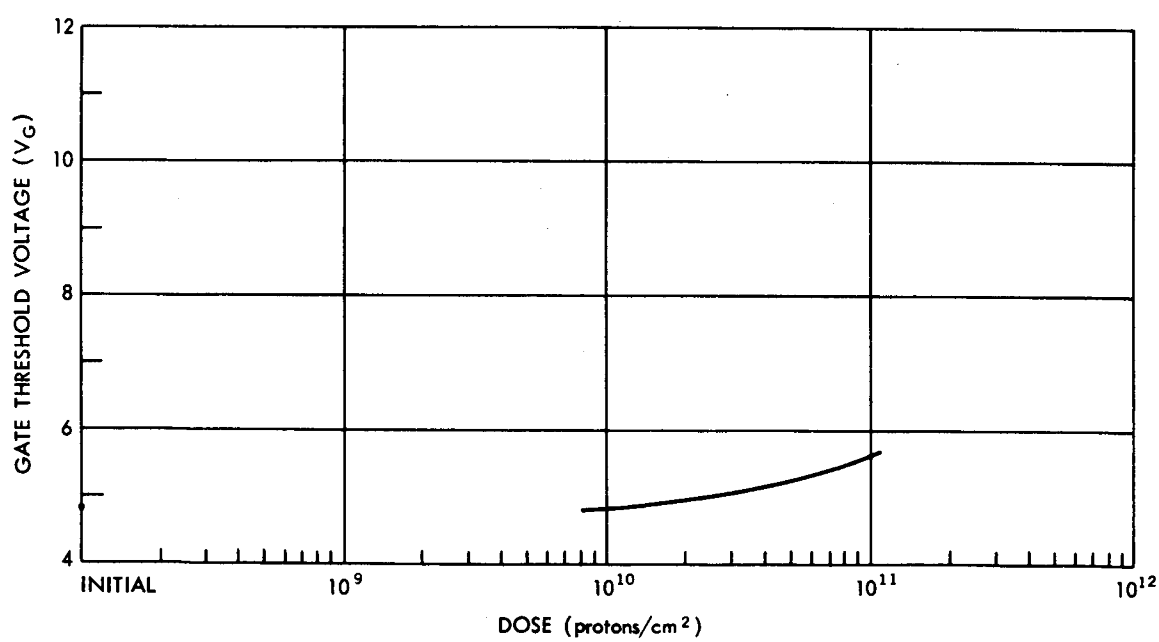

Figure IV.28. Unit C13 (SC1129) −6.6 Volts Gate Bias and 100 μa Drain Current During Exposure.

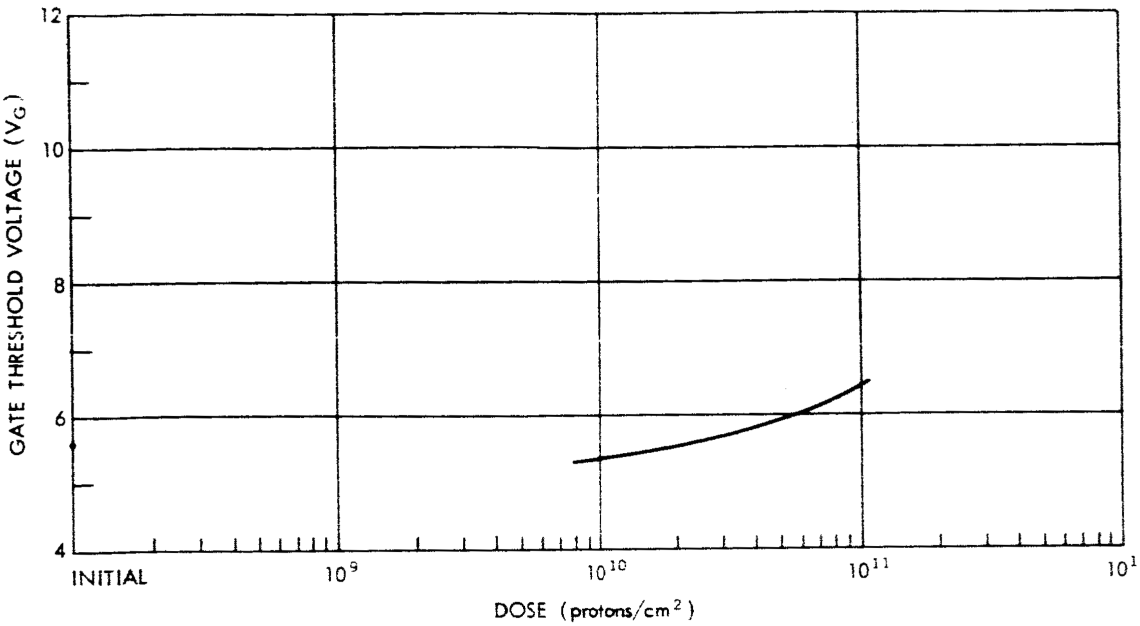

Figure IV.29. Unit C9 (SC1128) –6.6 Volts Gate Bias and 100 μa Drain Current During Exposure.

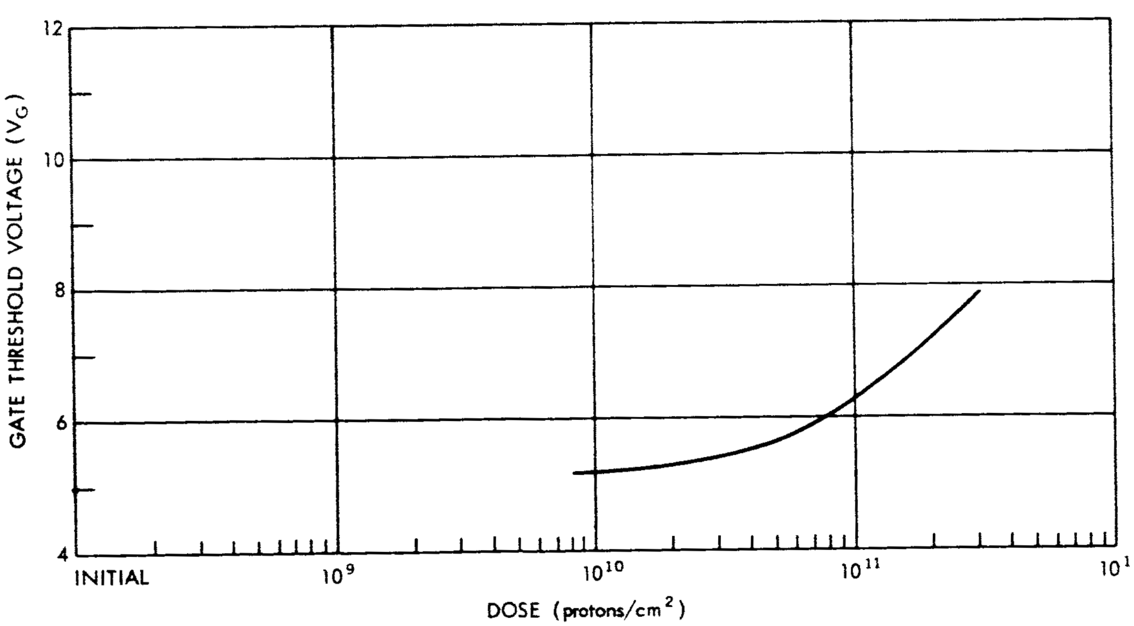

Figure IV.30. Unit C6 (SC1128) –10 Volt Gate Bias and 100 μa Drain Current During Exposure.

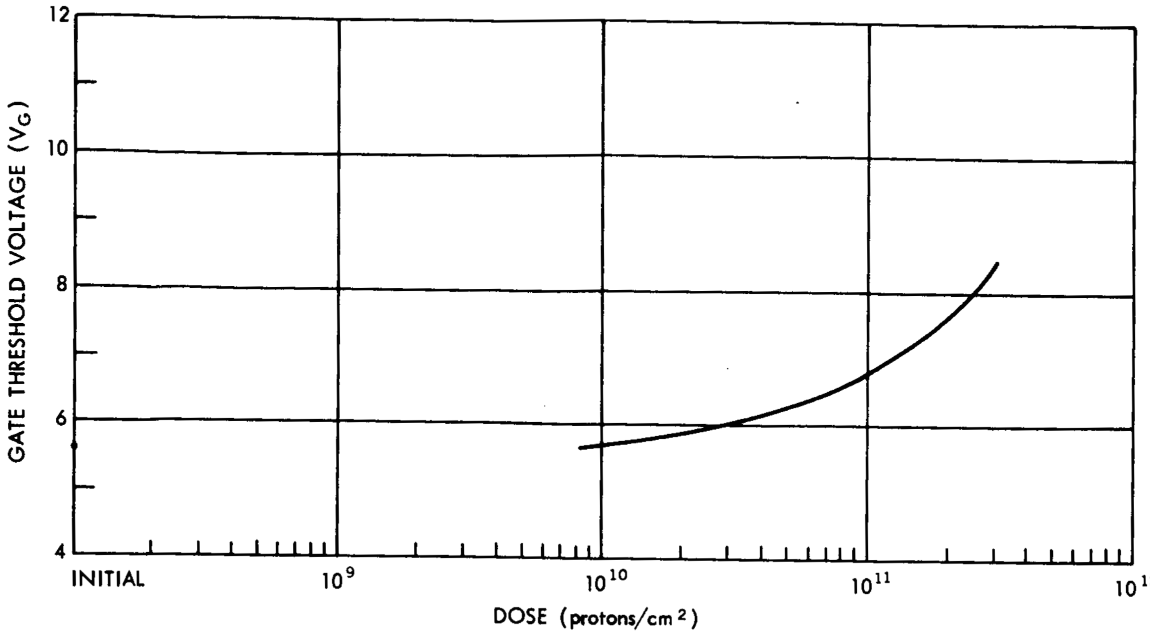

Figure IV.31. Unit C7 (SC1128) −10 Volts Gate Bias and 100 μa Drain Current During Exposure.

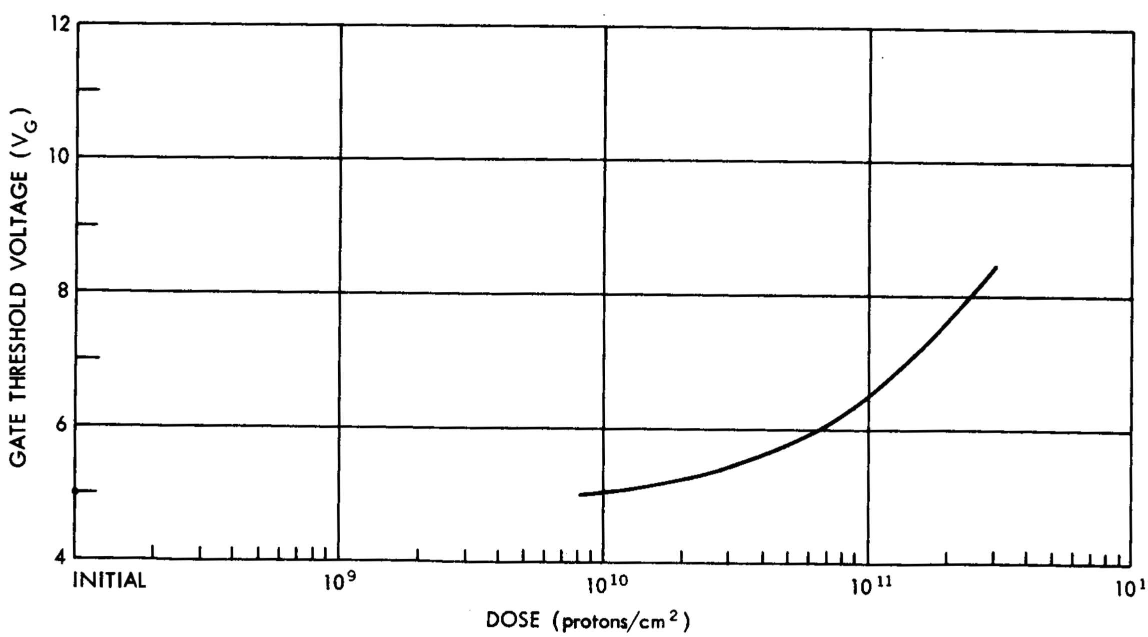

Figure IV.32. Unit C8 (SC1128) −10 Volts Gate Bias and 100 μa Drain Current During Exposure.

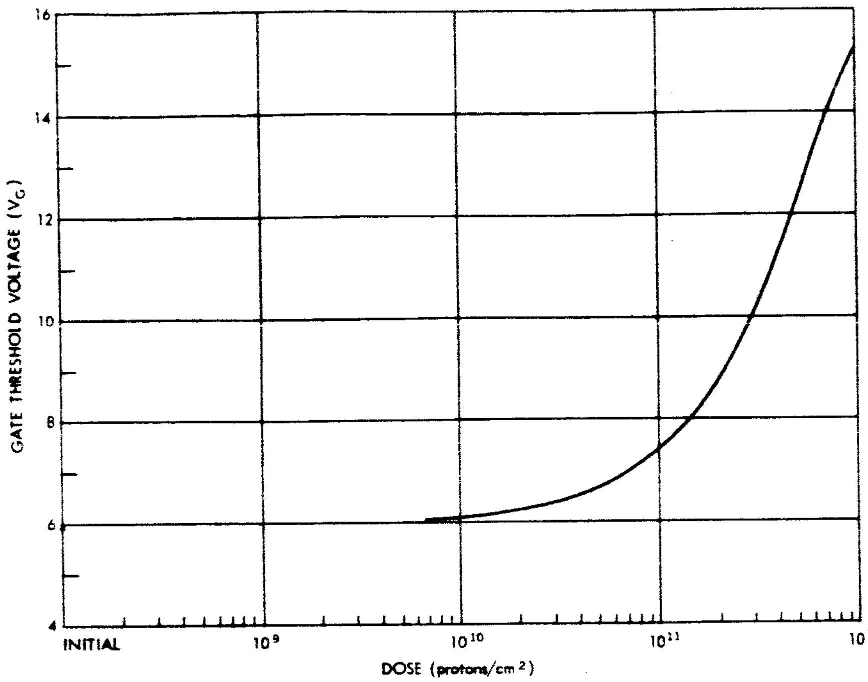

Figure IV.33. Unit C5 (SC1128) −20 Volts Gate Bias and 100 μa Drain Current During Exposure.

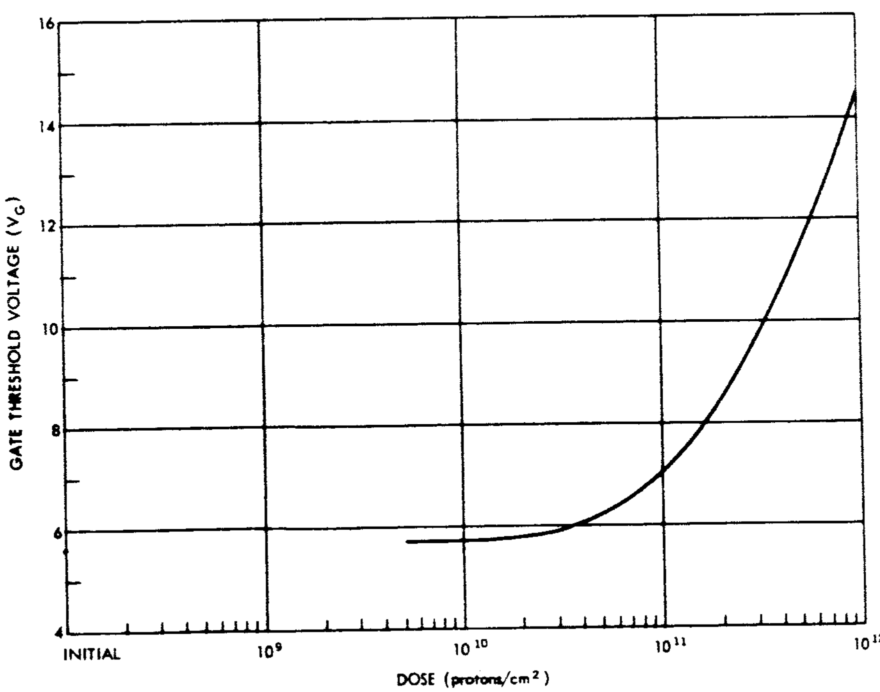

Figure IV.34. Unit C3 (SC1128) −20 Volts Gate Bias and 100 μa Drain Current During Exposure.

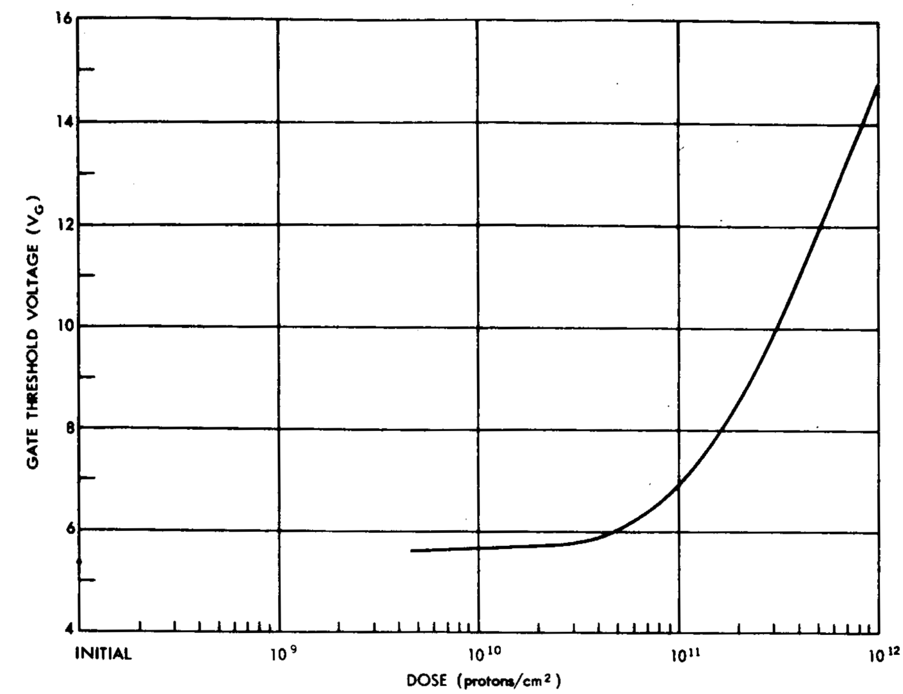

Figure IV.35. Unit C4 (SC1128) –20 Volts Gate Bias and 100 μa Drain Current During Exposure.

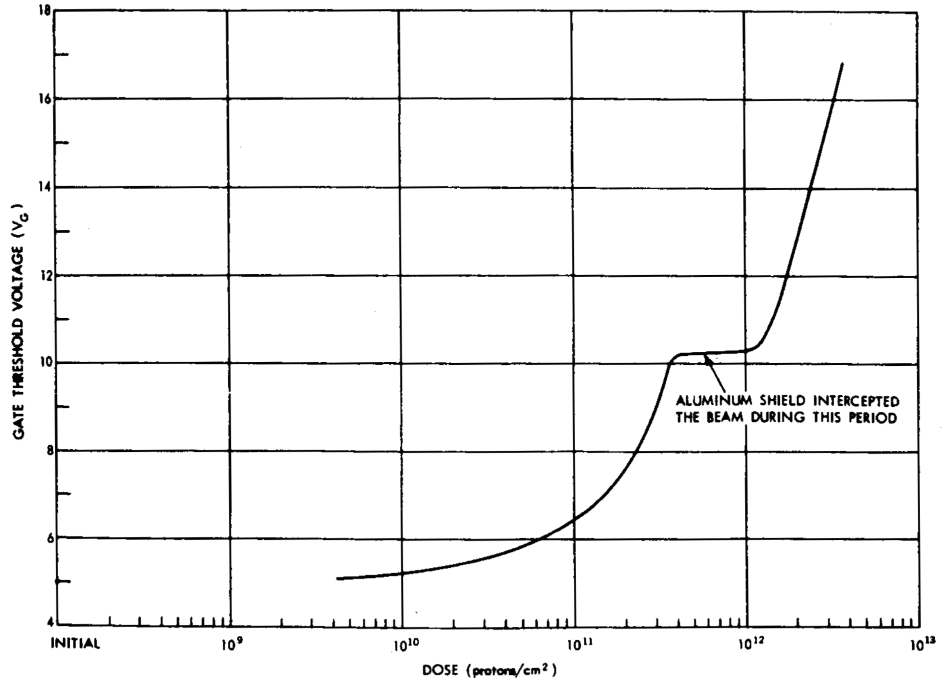

Figure IV.36. Unit C1 (SC1128) –20 Volts Gate Bias During Exposure 100 μa Drain Current During Exposure.

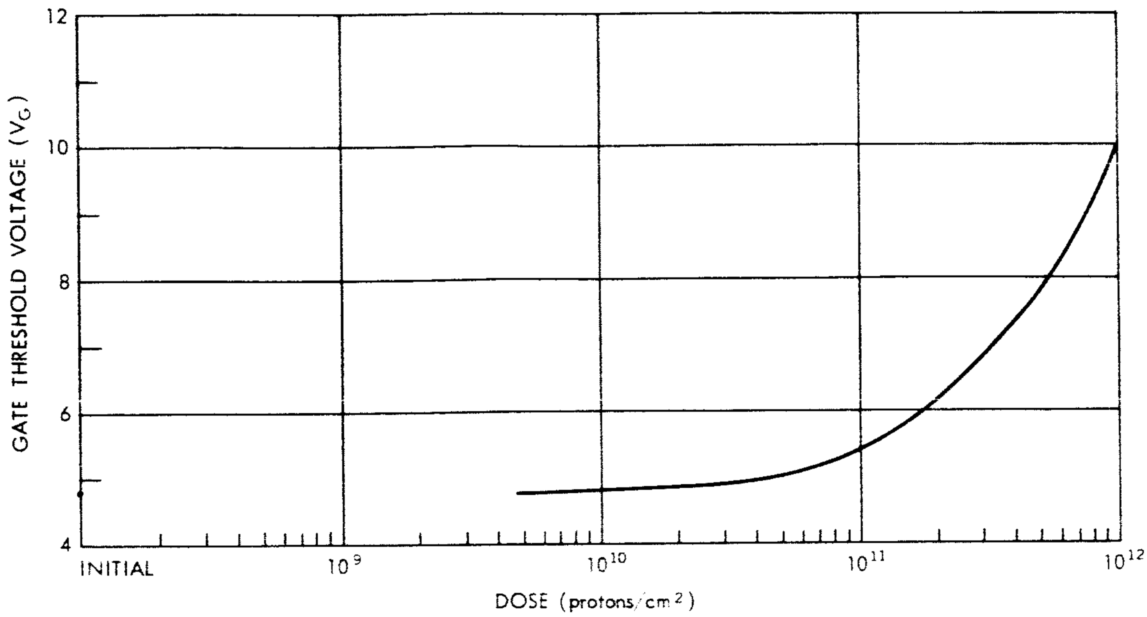

Figure IV.37. Unit C2 (SC1128) −20 Volts Gate Bias and 100 μa Drain Current During Exposure. (Device Not Centered in Beam)

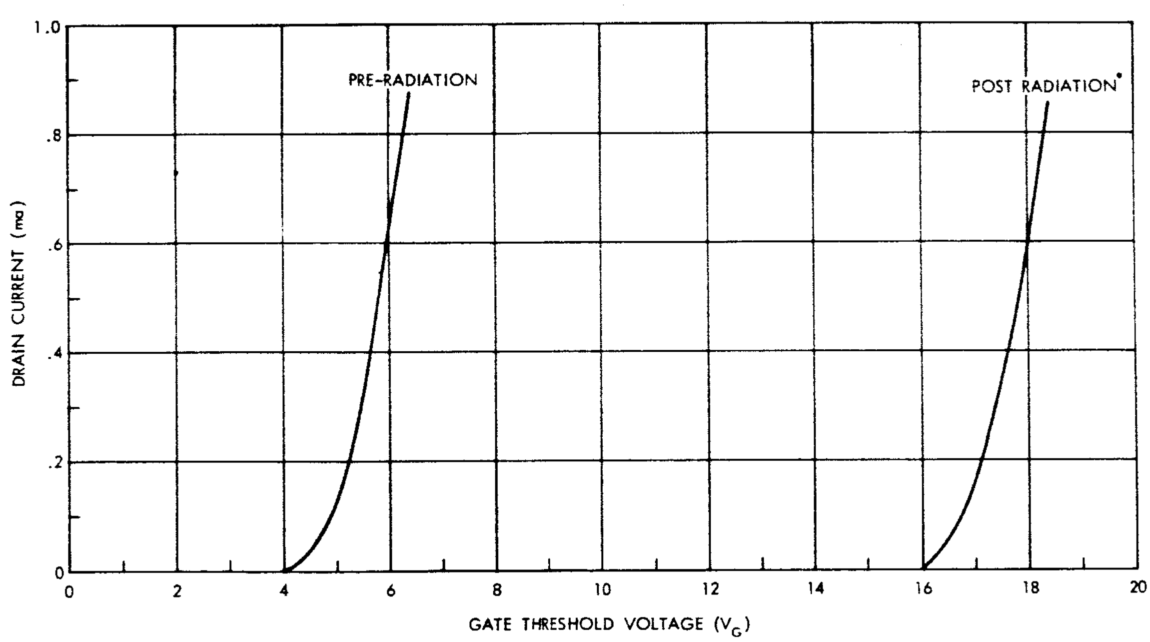

Figure IV.38. Unit C1 Gate 1.

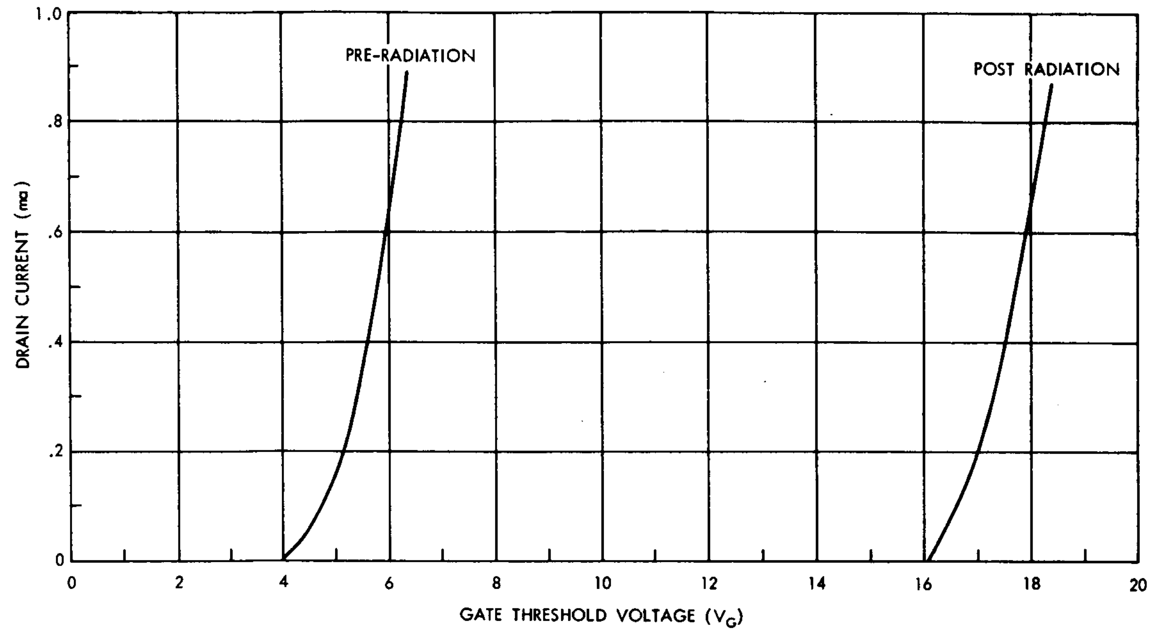

Figure IV.39. Unit C1 Gate 2.

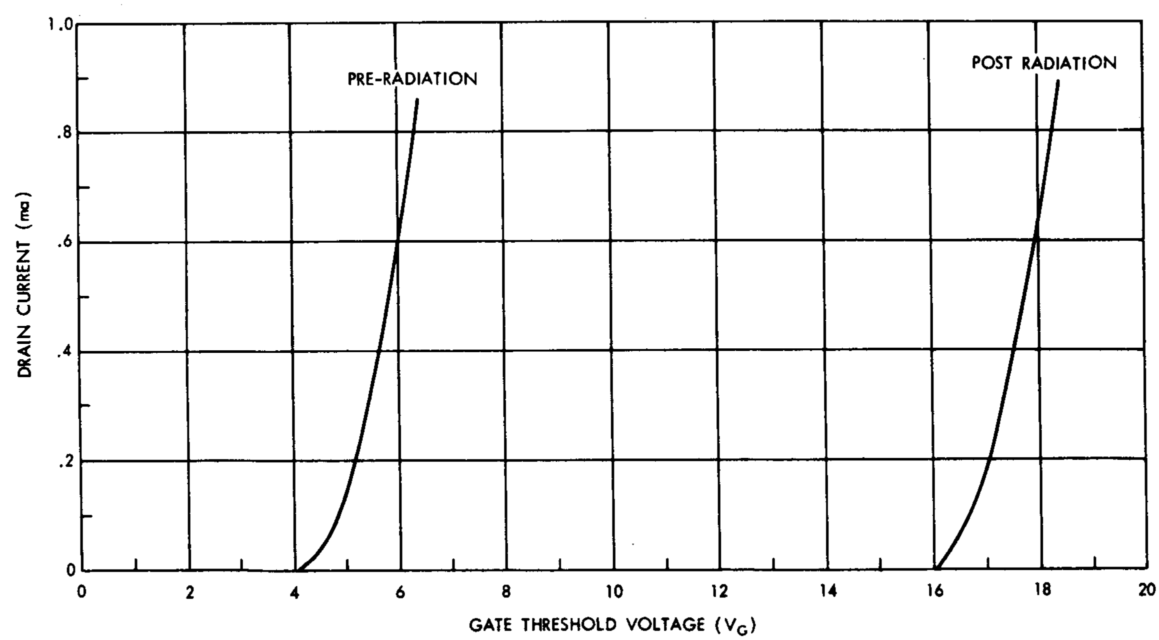

Figure IV.40. C1 Gate 3.

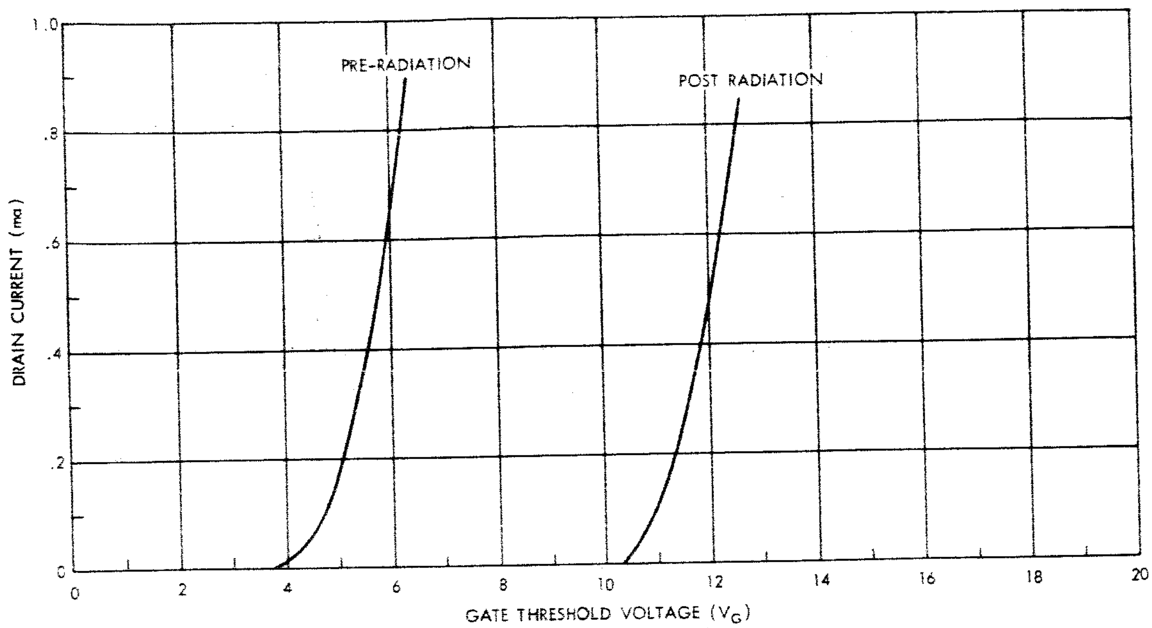

Figure IV.41. Unit C2 Gate 1.

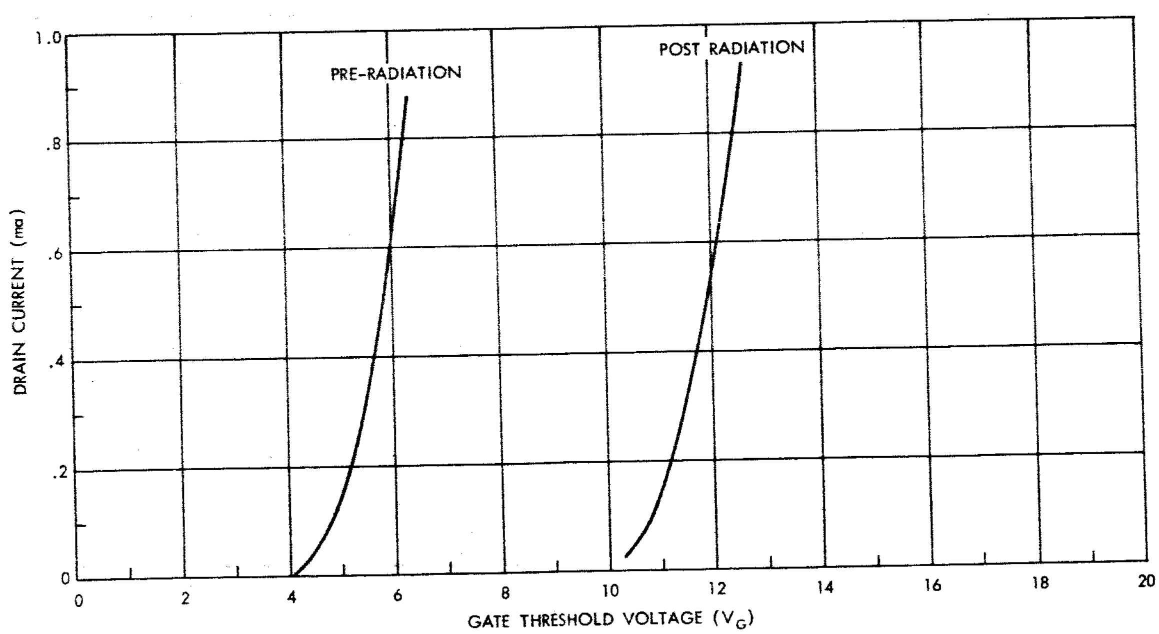

Figure IV.42. Unit C2 Gate 2.

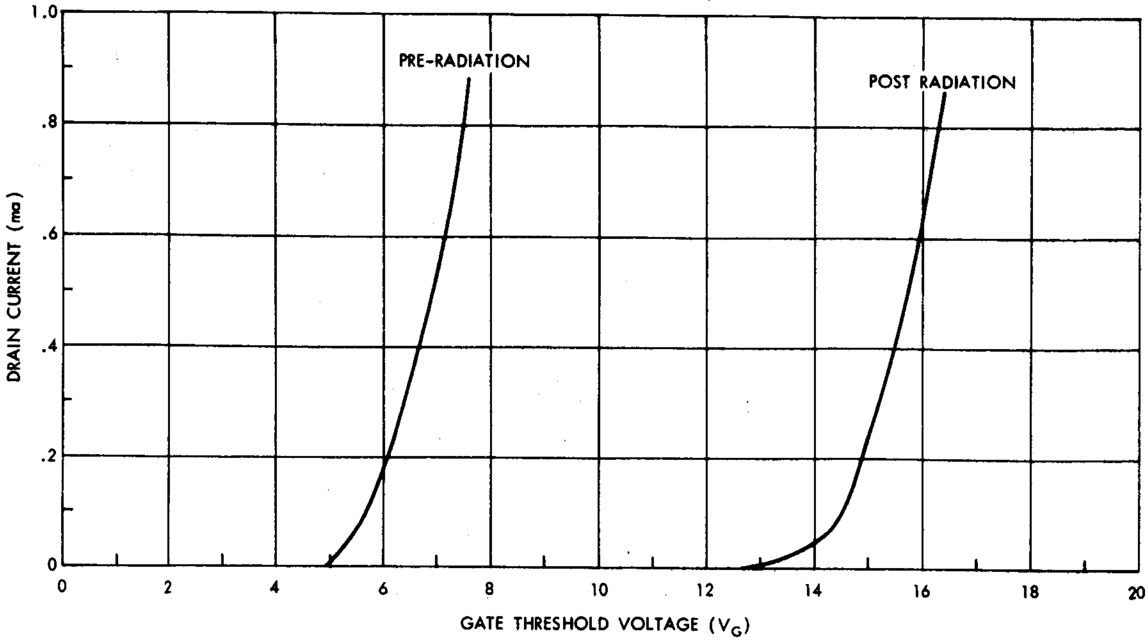

Figure IV.43. Unit C3 Gate 1.

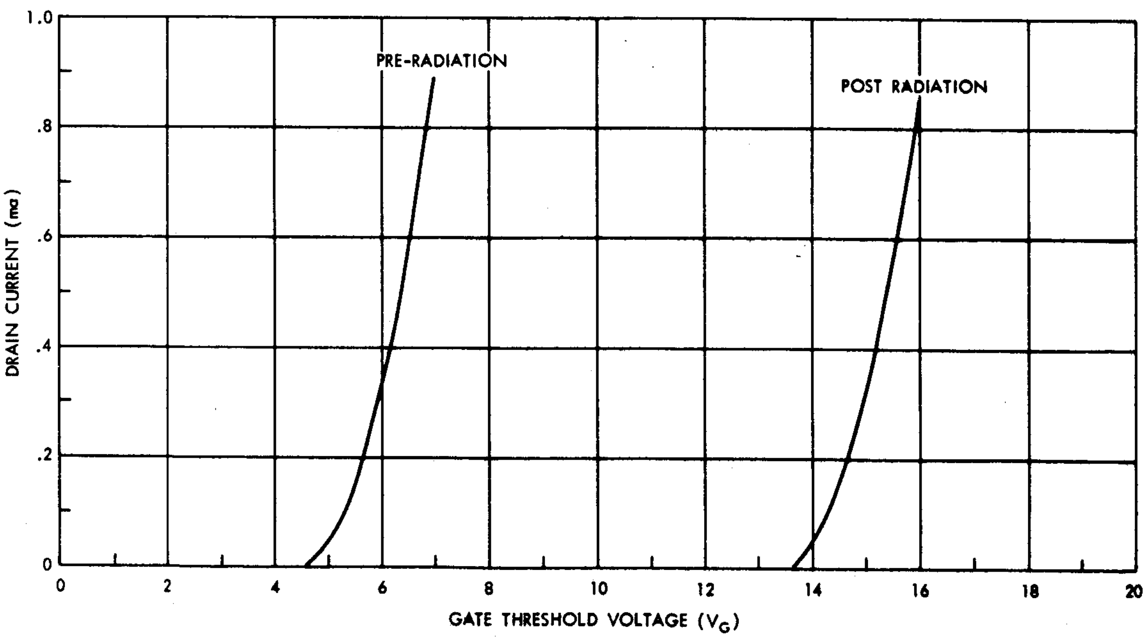

Figure IV.44. Unit C4 Gate 1.

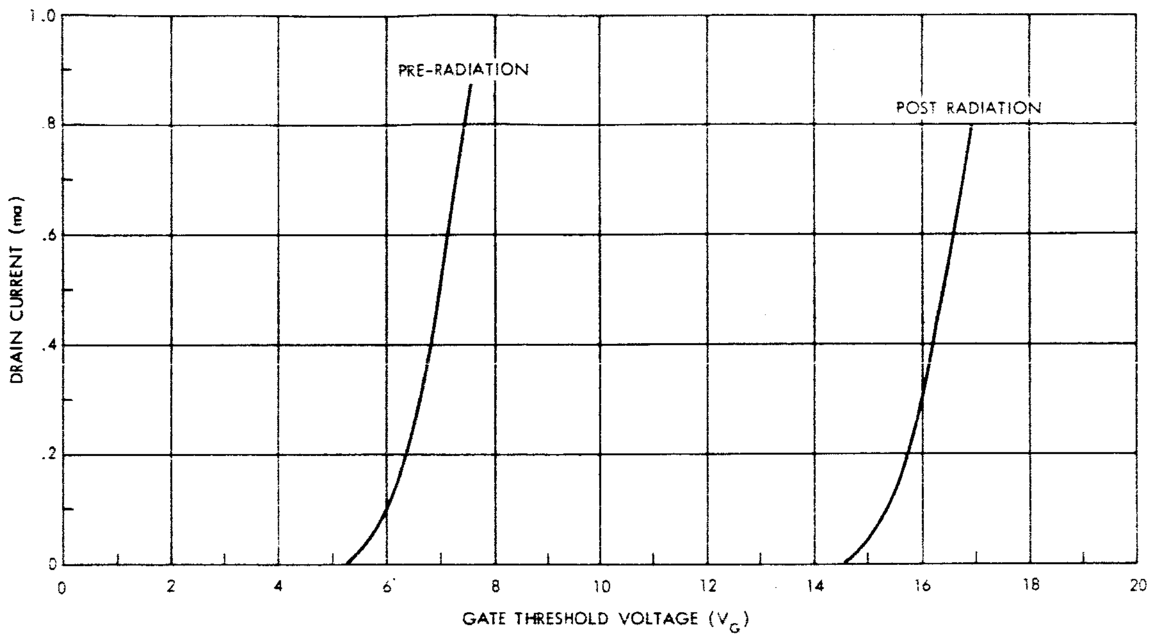

Figure IV.45. Unit C5 Gate 1.

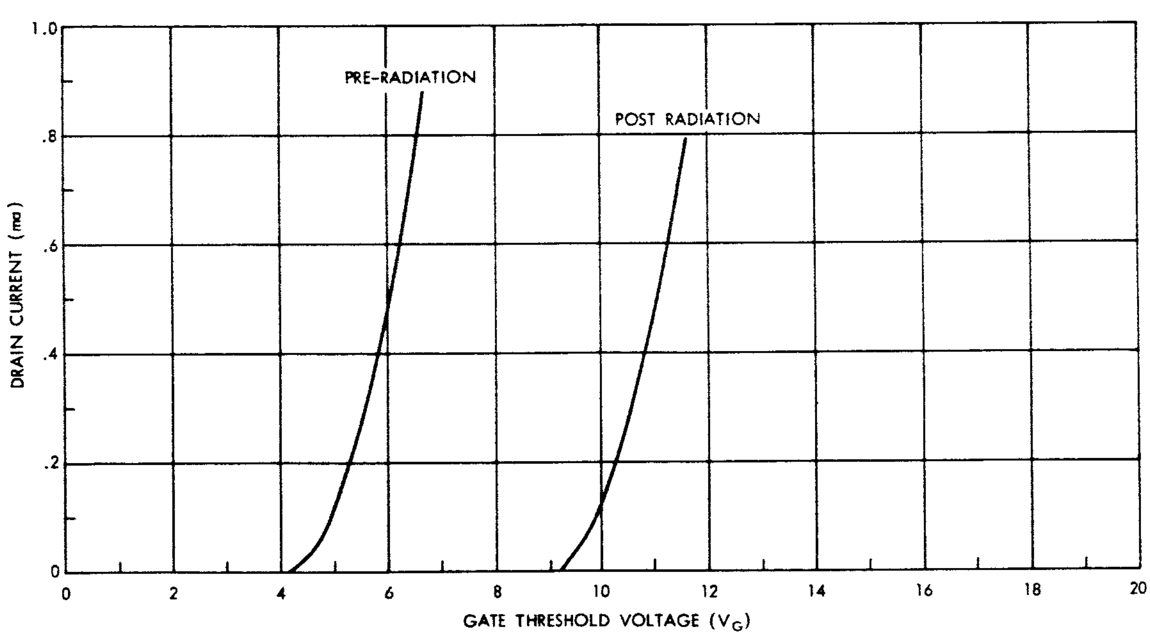

Figure IV.46. Unit C6 Gate 1.

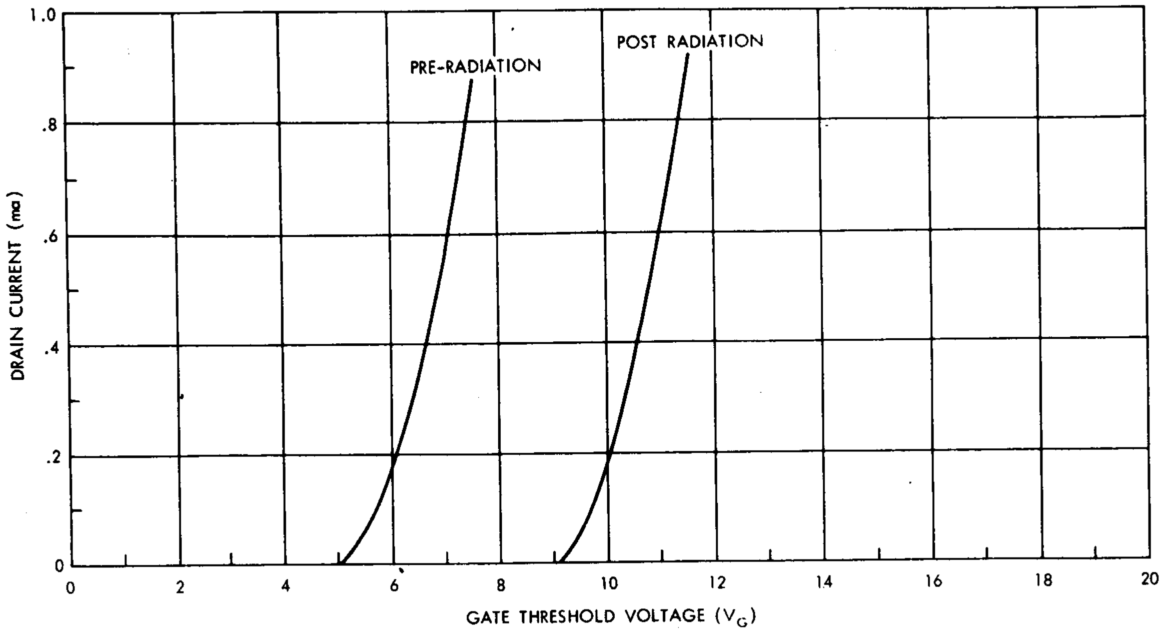

Figure IV.47. Unit C7 Gate 1.

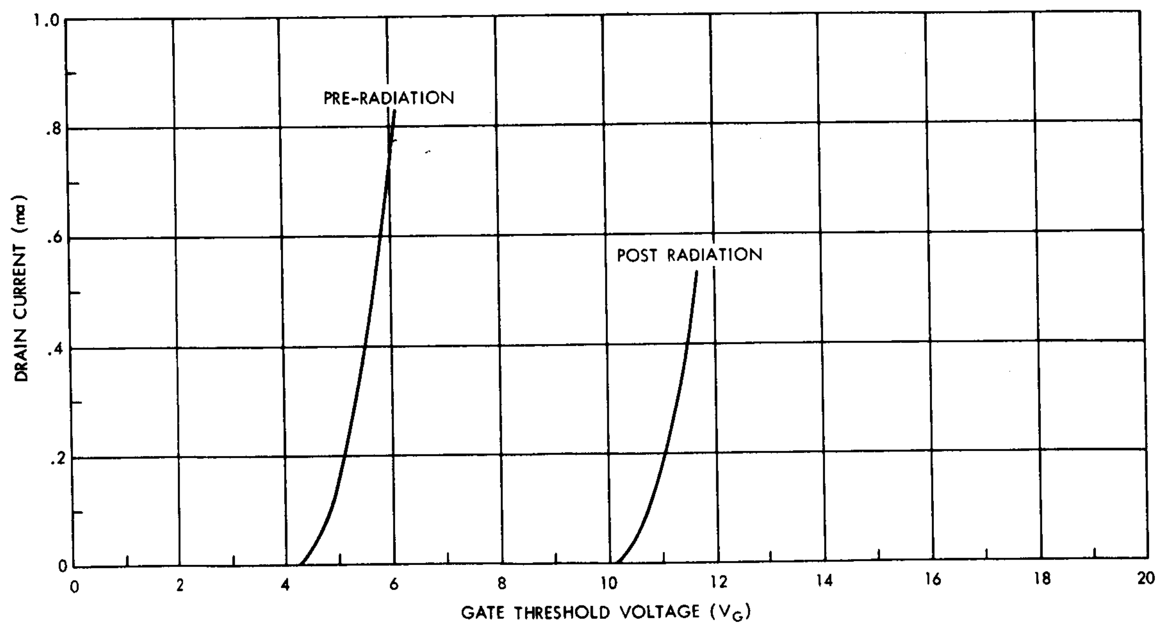

Figure IV.48. Unit C8 Gate 1.

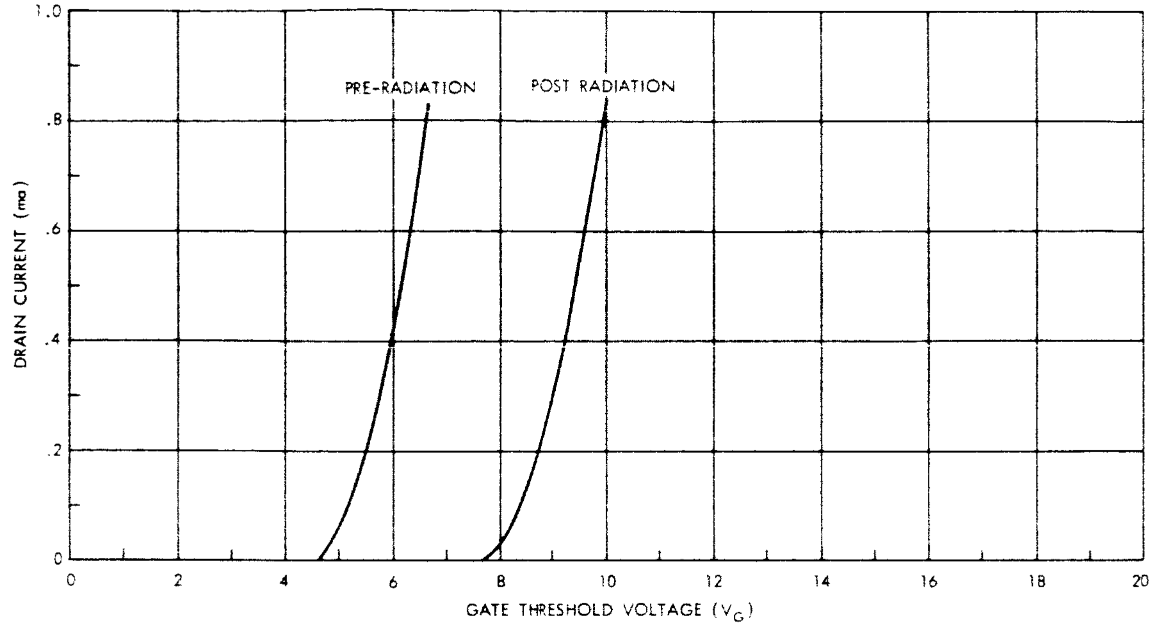

Figure IV.49. Unit C9 Gate 1.

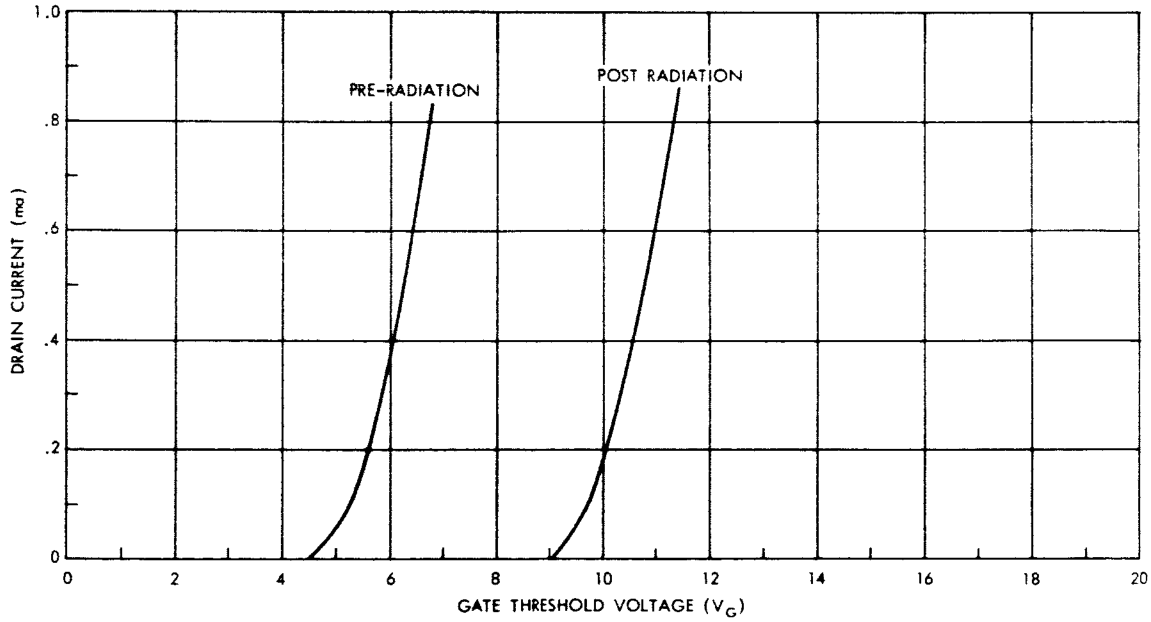

Figure IV.50. Unit C10 Gate 1.

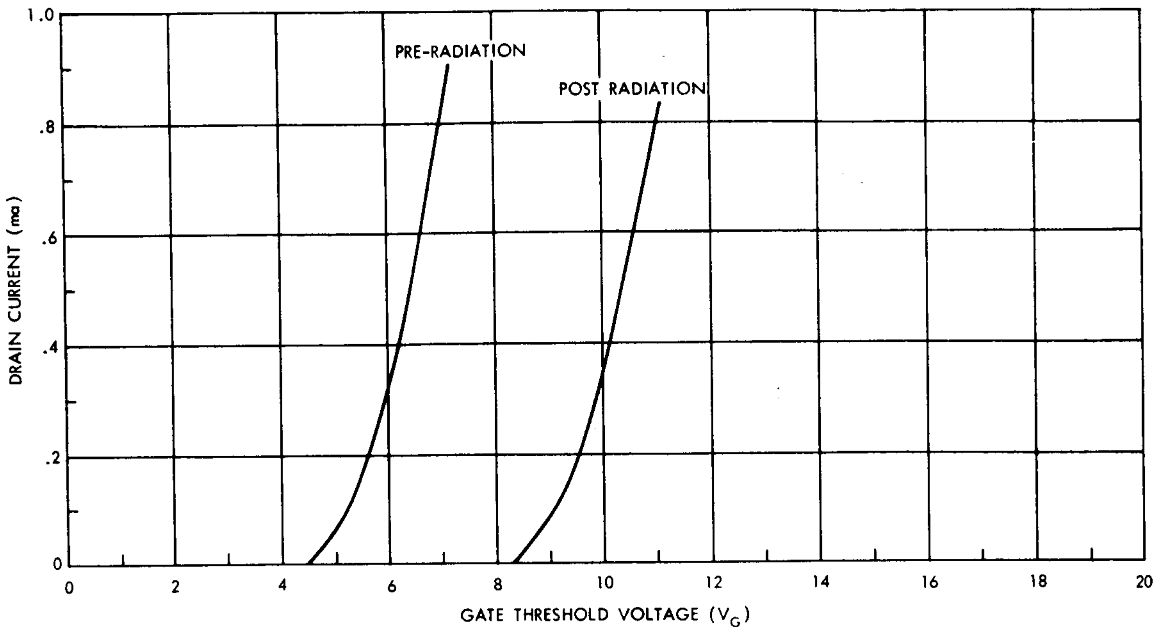

Figure IV.51. Unit C11 Gate 1.

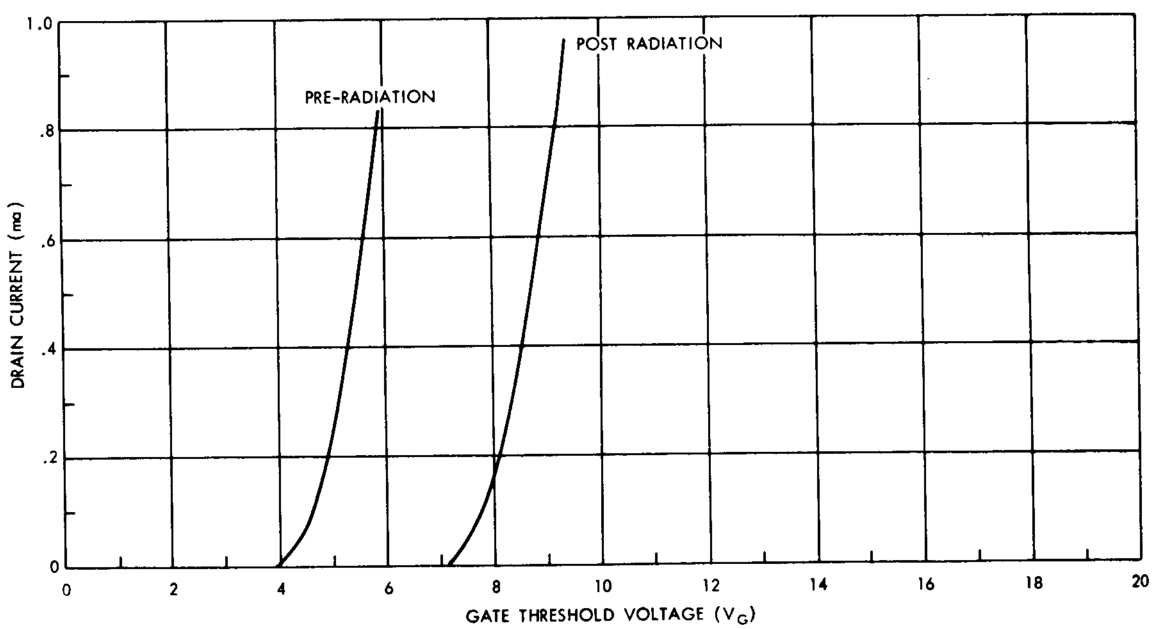

Figure IV.52. Unit C13 Gate 1.

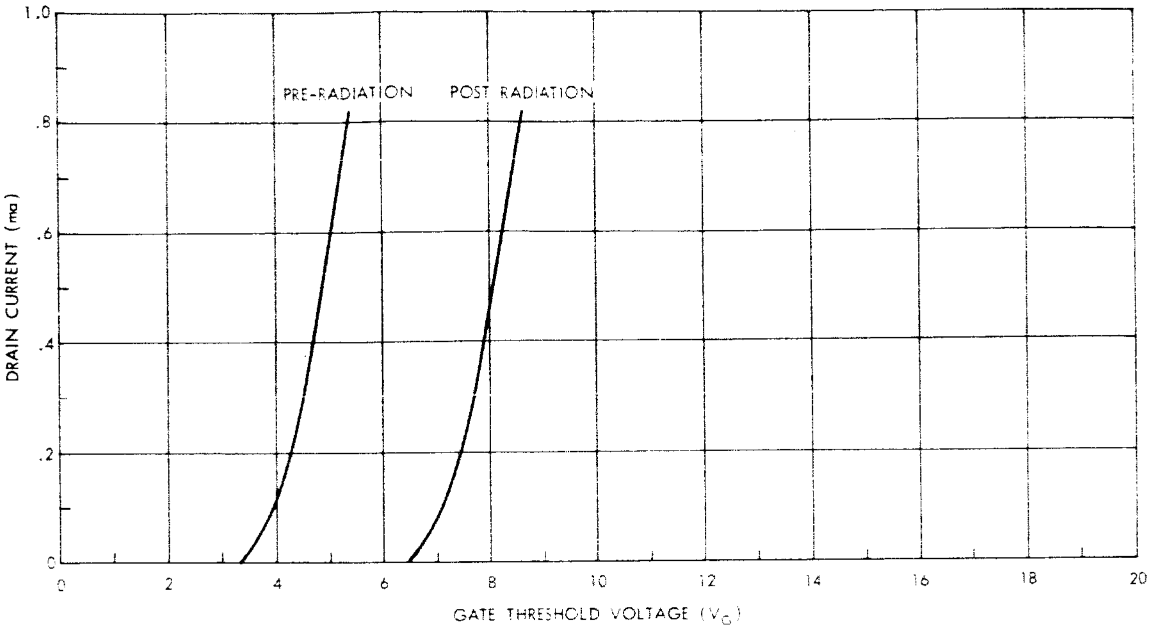

Figure IV.53 Unit C14 Gate 1.

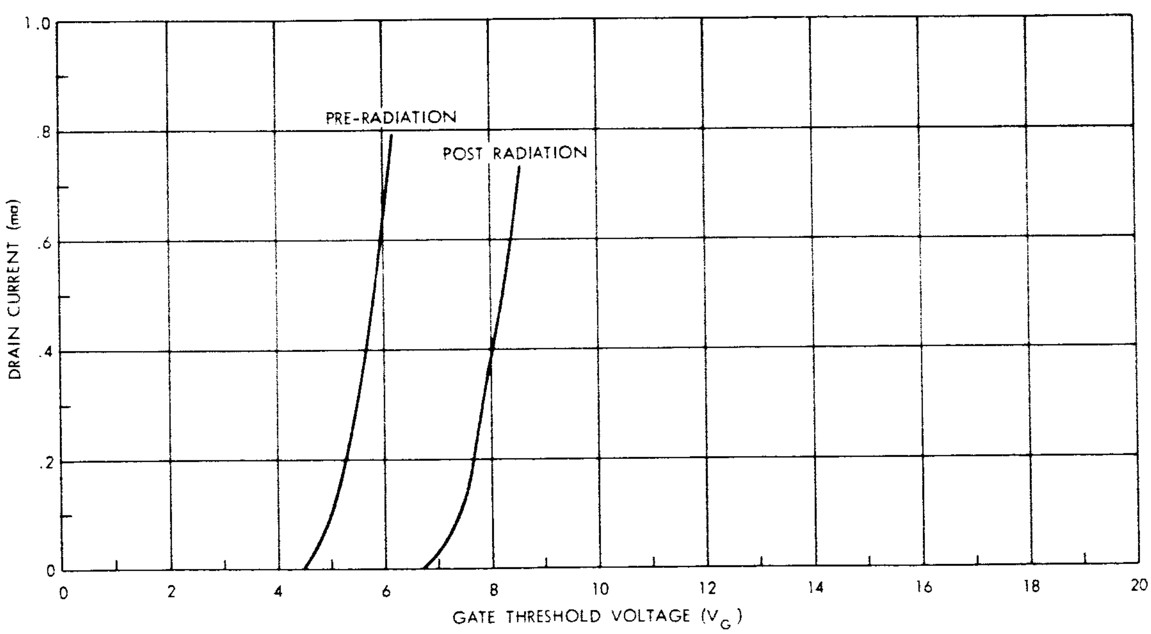

Figure IV.54. Unit C15 Gate 1.